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SPECIFICATION

OPTICAL COMMUNICATIONS SYSTEM USING OPTICAL
FREQUENCY CODES, AND OPTICAL TRANSMITTER, OPTICAL
5      RECEIVER AND REFLECTIVE OPTICAL COMMUNICATION
EQUIPMENT THEREFOR

TECHNICAL FIELD

[0001]   Of the present invention relates to an optical communications system
that utilizes the OCDM (Optical Code Division Multiplex), QPSK

10    (Quadrature Phase Shift Keying), or QAM (Quadrature Amplitude
Modulation) technique which multiplexes plural data sequences into a single
data sequence that can be demultiplexed by use of different optical codes;
furthermore, the invention pertains to an optical transmitter, an optical
receiver and reflective optical communication equipment for use in the optical

15    communications system.

Background Art

[0002]   With respect to a point-to-multipoint transmission on the PON
(Passive Optical Network) wherein two or more local offices are connected
via optical fibers to a central office, there has been proposed a scheme

20    according to which: each local office is assigned pseudo-random spreading
codes orthogonal to each other, and modulates an optical signal in accordance
with the spreading codes assigned thereto and transmits the modulated optical
signal; and the central office multiplexes such optical signals from the
respective local offices and transmits over a long distance.   A description

25    will be given below of a conventional technique for optical frequency coding
in an optical frequency region by use of the spreading codes.

Fig. 1 schematically shows the configuration of one channel and

optical frequency coding (wavelength coding) in the optical code division multiplex communications system. At the transmitting side, a broadband optical signal 20 is emitted from a light source 10 for incidence to an encoder 11, which performs wavelength coding of the incident optical signal by

5     permitting the passage therethrough of only wavelength components corresponding to selection wavelength components 31 of the encoder 11, providing an coded optical signal 21. The thus coded optical signal 21 is transmitted over an optical fiber 13 to a decoder 12 at the receiving side. The decoder 12 similarly permits the passage therethrough of only those

10     codes of the optical signal 21 from the corresponding encoder 11 which are selected according to selection wavelength components 32 of the decoder, providing a decoded optical signal 22.

[0003] On the other hand, as shown in Fig. 1(c), when an optical signal is input to the decoder 12 from an encoder which does not correspond to the

15     decoder and the input optical signal contains wavelength components 21' based on the selection wavelength components 31' of the encoder, all chips (optical frequencies or wavelengths) of the input optical signal are not allowed to pass through the decoder 12 according to its selection wavelength components 32; even if allowed to pass, some chips of the input optical signal

20     are allowed, and hence the optical signal is not decoded into an appropriate optical signal but instead becomes an optical noise 22'. The encoder 11 and the decoder 12 mentioned herein are disclosed in non-patent document 1, for instance.

The wavelengths for use by the conventional encoder and decoder are

25     specific for them, and the wavelength of the input optical signal 20 to the encoder 11 and the selection wavelength 31 of the encoder 11 are not allowed, in almost all cases, to deviate from their predetermined absolute wavelengths.

This raises a problem that the receiving side is required to notify the transmitting side of the wavelength of the optical signal to be sent and the selection wavelength 31 of the encoder 11, whereas the transmitting side is required to calibrate the wavelength 20 of the light source 10 and the selection wavelength 31 of the encoder 11 in response to the notification.

[0004] A solution to this problem is proposed, for example, in non-patent document 2 and patent document 1 (issued February 2, 1999). With the proposed method, light emitted from a broadband light source which has a wavelength width of several dozen nanometers, such as LED (Light Emitting Diode), is input to a Mach-Zehnder or Fabry-Perot filter made of a material with less temperature dependence of its selection wavelength, wherein the input light is subjected to wavelength coding by the selection of its wavelength through use of sine functions; that is, data sequences are each assigned a wavelength with a different period.

In conventional optical communications, a binary data sequence is transmitted using an intensity modulation scheme that represents the presence or absence of an optical signal, depending on whether the value of each piece of data sequence is a space or mark.

[0005] A proposal has also been made to apply a four-phase modulation technique now in use in radio communications to optical communications as well. This technique is to convert the optical phase of an optical signal of one wavelength into one of four predetermined phases in accordance with two data sequences.

For optical transmission of two or more data sequences in multiplexed form there are available an "Optical FDM (Optical Frequency Division Multiplex) or WDM (Wavelength Division Multiplex) method. In WDM-PON employing the optical wavelength division multiplex method, it

is necessary to adjust the wavelengths of optical signals to be sent from respective local offices to ensure accurate signal multiplexing and demultiplexing. To avoid such wavelength adjustment, there has been proposed an optical communications system in which each local office

5 modulates, according to data sequence, an optical signal received from the central office and sends back thereto the modulated optical signal (see, for instance, non-patent documents 3 and 4).

[Patent Document 1] Japanese Patent Application Kokai Publication No. H11-32029

10 [Non-Patent Document 1] Saeko Oshiba et al., "Experimental Study on Bit Rate Enhancement Using Time-Spread/Wavelength-Hop Optical Code Division Multiplexing," 2002 Annual General Conference of the Institute of Electronics, Information and Communication Engineers of Japan, B-10-80

[Non-Patent Document 2] T. Pfeiffer et al., "High Speed Optical
15 network for Asynchronous Multiuser Access Applying Periodic Spectral Coding ofBroad Band Sources," vol. 33, No. 25, pp. 2441-2442, 1997, Electronics Letters

[Non-Patent Document 3] Takeshi Imai et al., "The Inter-Operability of WDN-PON System ONU Using a Reflective SOA," 2002 Society
20 Conference of the Communications Society of the Institute of Electronics, Information and Communication Engineers of Japan, B-10-50

[Non-Patent Document 4] Satoshi Narukawa et al., "Transmission Characteristics of Wavelength Channel Data Rewriter Using Semiconductor Optical Amplifier," 2003 Society Conference of Communication Society of
25 the Institute of Electronics, Information and Communication Engineers of Japan, B-10-51

DISCLOSURE OF THE INVENTION

## PROBLEM TO BE SOLVED BY THE INVENTION

[0006] The prior art disclosed in documents 2 and 3 refers to OCDM (Optical Code Division Multiplexing) in which data sequences are each assigned a wavelength selected with a different period equivalent to a code, but since

5    these optical codes corresponding to each data sequence (channel) are not mutually orthogonal to each other, the code assignment in a narrow optical frequency width containing a small number of periods causes interference between the optical signals, resulting in a drop in their S/N (Signal/Noise). For example, letting the optical frequency difference to be assigned to the first

10   data sequence and a reference optical frequency wavelength be represented by $\lambda 1$ and $\lambda 0$, respectively, a code is assigned over a wide optical frequency width including not only one period of optical frequencies $\lambda 0$ to $\lambda 0 + \lambda 1$ but also multiple periods of optical frequencies $\lambda 0$ to $\lambda 0 + 2\lambda 1$, $\lambda 0$ to $\lambda 0 + 3\lambda 1$ ...; a code is assigned to the second data sequence over a wide optical frequency

15   width including not only one period of optical frequencies $\lambda 0$ to $\lambda 0 + \lambda 2$ but also multiple periods of optical frequencies $\lambda 0$ to $\lambda 0 + 2\lambda 2$, $\lambda 0$ to $\lambda 0 + 3\lambda 2$ ...; and a code is assigned to the third data sequence over a wide optical frequency width including not only one period of optical frequencies $\lambda 0$ to $\lambda 0 + \lambda 3$ but also multiple periods of optical frequencies $\lambda 0$ to $\lambda 0 + 2\lambda 3$, $\lambda 0$ to

20   $\lambda 0 + 3\lambda 3$ ...; and codes are similarly assigned thereafter.   In this way, the prior art improves S/N.

[0007] With the above method, however, when the number of wavelengths to be selected with the period of a sine function is small, inter-channel interference between optical signals is not negligible, so that it is difficult to

25   multiplex channel optical signals corresponding to many data sequences without degradation of the bit error rate.   To suppress the inter-channel interference between optical signals, the wavelength width of the light to be

emitted from the light source needs to be wide so as to multiplex wavelengths of a number sufficiently large to approximate the wavelength width to infinity. The use of a broadband light source gives rise to the problems of waveform degradation and limitation on the transmission bandwidth due to the influence

5    of wavelength dispersion on the transmission line, leading to the impossibility of high-speed transmission.    Since light of a wide frequency width is required, the wavelength dispersion degrades the signal-to-noise ratio in the case of long-distance transmission.    Further, separation of channels only by the sine-function period makes it impossible to increase the number of

10   channels in the condition that the frequency width of the light to be emitted from the light source and the optical frequency selectable by a filter are limited.

[0008] In the case of controlling the optical phase of an optical frequency signal according to a modulation signal (data) by the application to the optical

15   communication of the four-phase modulation technique actually used in conventional radio communications, it is difficult at present to control the optical phase with accuracies on the order of tens of nanometers which is a few tenth of micrometer for the optical wavelength and hence is sufficiently accurate.

20        In the optical wavelength division multiplex PON disclosed in non-patent document 3, the optical signal that is used in the local office to send data to the central office is sent in non-modulated continuous light form from the central office to the local office.    Since the transmission of this non-modulated continuous light from the central to local office is not utilized

25   for information transmission, the information transmission efficiency is low accordingly.    The equipment set forth in non-patent document 4 does not transmit such non-modulated continuous light from the central office, and

hence it is better in information transmission efficiency than the equipment of non-patent document 3, but the central office sends a downstream optical signal of a low extinction ratio and the local office reuses the downstream optical signal of low extinction ratio for an upstream optical signal for

5 information transmission. Hence, the downstream optical signal of low extinction ratio impairs the communication quality.

MEANS FOR SOLVING THE PROBLEM

[0009] The present invention has first through third aspects, each of which uses a function $C_i(f)$ of an i-th code and its complementary function $(1-C_i(f))$,

10 which satisfy the following conditions:

Function $C_i(f)$ is a periodic function which satisfies $C_i(f)=C_i(f+FSR_i)$, and the function $C_i(f)$ takes the value in the range of 0 to 1;

Optical frequency width FSR is an optical frequency width that is a common multiple of a repetition period of the function of each code in the

15 range from a predetermined optical frequency Fst to a predetermined optical frequency Fla;

The complementary function of the function $C_i(f)$ is a function $(1-C_i(f))$ obtained by subtracting the function $C_i(f)$ from 1, and the functions $C_i(f)$ and $(1-C_i(f))$ bear the relationship $\int C_i(f) \cdot C_i(f)df > \int C_i(f) \cdot (1-C_i(f))df$,

20 where $\int df$ is a definite integral with respect to f for an arbitrary interval FSR from Fst to Fla; and

Function $C_i(f)$, a function $C_j(f)$ of an arbitrary j-th code except an i-th one, and the complementary function $(1-C_j(f))$ of the function $C_j(f)$ bear the relationship $\int C_i(f) \cdot C_j(f)df = \int C_i(f) \cdot (1-C_j(f))df$.

25 [0010] According to the first aspect of the present invention that is applied to optical code communication:

the transmitting side generates and transmits, for each piece of data of

a binary data sequence, an optical code signal whose optical intensity-frequency characteristic is at least one of the function $Ci(f)$ and its complementary function $(1-Ci(f))$ both corresponding to the value of each piece of data of the i-th binary data sequence, at least over the enough wide

5    period FSR that satisfies orthogonal relation between the functions; and

the receiving side regenerates from received optical signal a first intensity difference signal corresponding to the difference between a first intensity signal, corresponding to the optical intensity of an optical signal whose optical intensity-frequency characteristic is $Ci(f)$ based on the function

10    $Ci(f)$, and a second intensity signal corresponding to the optical intensity of an optical signal whose optical intensity-frequency characteristic is $(1-Ci(f))$ based on the complementary function $(1-Ci(f))$; and regenerate the data sequence from the first difference signal.

[0011] According to the second aspect of the present invention which

15 ·  performs, for example, pseudo-orthogonal phase modulation:

and let $\Delta f$ represent the remainder of the division of an arbitrary optical frequency width equal to or narrower than the optical frequency width FSR by the repetition period $FSRi$ of the function $Ci(f)$ , let a phase $2\pi(\Delta f/FSRi)$ represent a phase difference from the function $Ci(f)$, and let

20    $Ci'(f)$ $(=Ci(f+\Delta f))$ represent a function with an optical frequency $(f+\Delta f)$ different by said remainder $\Delta f$ from the optical frequency of the function $Ci(f)$ of the i-th code, the function $Ci'(f)$, the function $Cj(f)$ and its complementary function $(1-Cj(f))$ bear the relationship:

$$\int Ci'(f) \cdot Cj(f)df = \int Ci'(f) \cdot (1-Cj(f))df;$$

25    the transmitting side separates a binary data sequence into multiple data sequences, then generates an optical signal whose optical intensity-frequency characteristic is at least one of the function and its

complementary function both corresponding to the value of each piece of data of each data sequence corresponding to each code and combines and transmits such optical signals as an optical code signal;

the receiving side detects, based on the functions corresponding to the above-said separated data sequences and their complementary functions, optical intensity differences between the optical signals having their optical intensity-frequency characteristics based on the above-mentioned functions, respectively, and regenerates the separated data sequences.

[0012] According to the third aspect of the present invention which is applied to reflective optical communication:

an optical signal whose optical intensity-frequency characteristic is the function $Ci(f)$ or its complementary function $(1-Cj(f))$ is input at least the optical frequency width FSR, the input optical signal is input to an encoder whose filtering optical frequency characteristic is based on the function $Ci(f)$ and which outputs an optical signal, and the input optical signal is input as well to a complementary encoder whose filtering optical characteristic is based on the complementary function $(1-Ci(f))$ and which outputs a complementary optical signal; and

optical signals and their complementary optical signals are selectively combined according to each piece of data of the input binary data sequence and transmitted as an optical code signal.

[EFFECT OF THE INVENTION]

[0013] According to the configuration of the first aspect of the present invention, the function $Ci(f)$ is continuously repeated, and if it is within a frequency range from Fst to Fla, optical code signals of the optical frequency width FSR at an arbitrary position need only to be transmitted; therefore, even if a drift occurs in the optical frequency for the light source and the encoder of

the optical transmitter and the decoder of the optical receiver, it is not

necessary to notify the transmitting side of the transmission optical frequency

from the receiving side and adjust the optical frequency at the transmitting

side accordingly. Furthermore, since the optical code signals whose optical

5     intensity-frequency characteristics Fi(f) are orthogonal to each other are used

for a plurality of data sequences, it is possible to multiplex many optical code

signals, in which case the optical frequency width of every optical code signal

needs only to be equal to FSR and there is no particular need for increasing

the optical frequency width.

10     [0014] According to the configuration of the second aspect of the present

invention, since the function of the optical intensity-frequency characteristic

is controlled for each piece of data of the separated data sequences, the

control accuracy for modulation may be appreciably lower than in the case of

modulating the optical phase of an optical frequency signal and the control

15     can easily be implemented.

According to the third aspect of the present invention, there is no need

for sending a non-modulated downstream optical signal that is sent back as an

upstream optical signal, and the optical intensity-frequency characteristic

functions of the downstream and upstream optical signals are orthogonal to

20     each other; hence, irrespective of whether the downstream data is mark or

space, it is possible to output the upstream optical signal of mark or space at

the same optical intensity--this does not lower the extinction ratio of the

downstream signal and hence precludes the possibility of the transmission

quality deteriorated.

25     BRIEF DESCRIPTION OF THE DRAWINGS

[0015] Fig. 1(a) shows an example of the system configuration of a

conventional optical code division multiplex method, Fig. 1(b) and Fig. 1(c)

show examples of light-source optical wavelength components, selection wavelength components of an encoded amount, its passage wavelength components, selection wavelength components of a decoder and its passage wavelength components;

Fig. 2 illustrates an example of the system configuration of a multiplex communications system to which the first mode of working of the present invention is applied, Figs. 2(a) and 2(b) showing its optical transmitter and optical receiver, respectively;

Fig. 3 illustrates another example of the multiplex communications system configuration to which the first mode of working of the invention is applied, Figs. 3(a) and 3(b) showing its optical transmitter and optical receiver, respectively;

Fig. 4 is a configuration illustrating an example of the communications system to which the first mode of working of the invention is applied;

Fig. 5(a) shows an example of a source frequency drift, Fig. 5(b) an example of an optical frequency region for encoding, and Fig. 5(c) an example of an optical frequency region for decoding;

Figs. 6(a), 6(b) and 6(c) are graphs showing examples of spreading codes in Embodiment 1, respectively;

Fig. 7 is a diagram illustrating an example of an encoder for use in Embodiment 2;

Fig. 8 is a diagram illustrating an example of a decoder for use in Embodiment 2;

Fig. 9 is a diagram illustrating an example of filters forming an encoder/decoder for use in Embodiment 2;

Fig. 10(a) is a diagram showing a first-order Hadamard matrix,

Fig.10(b) a diagram showing a second-order Hadamard matrix, and Fig. 10(c) a diagram showing a recurrence formula of the Hadamard matrix;

Figs. 11(a) and 11(b) are graphs showing examples of encoding codes (concatenated codes) corresponding to the second-order Hadamard matrix for use in Embodiment 3;

Fig. 12 is a diagram illustrating an example of a decoder for use in Embodiment 3;

Figs. 13(a), and 13(b) and 13(c) are diagrams showing, by way of example, source optical frequency component, optical frequency regions for encoding, encoded optical signals, optical frequency regions for decoding, and decoded optical signals in the cases where no source frequency drift occurs, and where the source frequency drift occurs, respectively, in Embodiment 3;

Fig. 14 is a diagram illustrating an example of a filter forming an encoder/decoder for use in Embodiment 2;

Fig. 15 is a diagram illustrating another example of the decoder for use in Embodiment 3;

Fig. 16 is a diagram illustrating another example of the filter forming an encoder/decoder for use in Embodiment 3;

Fig. 17 is a diagram illustrating still another example of the filter forming an encoder/decoder for use in Embodiment 3;

Fig. 18 is a diagram showing an example of a variable delay line for use in the filter forming the encoder/decoder in Embodiment 3;

Fig. 19 is a diagram showing another example of the variable delay line for use in the filter forming the encoder/decoder in Embodiment 3;

Figs. 20(a), and 20(b) and 20(c) are diagrams showing, by way of example, the relationships between source optical frequency component,

optical frequency regions for encoding, encoded optical signals, optical frequency regions for decoding, and decoded optical signals in the cases where no optical frequency regions for encoding drift occur, and where the source frequency and optical frequency regions for encoding drift occur,

5    respectively, in Embodiment 3;

Fig. 21 is a diagram illustrating still another example of the filter forming the encoder/decoder for use in Embodiment 3;

Fig. 22 is a diagram illustrating another example of the encoder for use in Embodiment 3;

10    Fig. 23 is a diagram illustrating another example of the decoder for use in Embodiment 3;

Fig. 24 is a diagram illustrating another example of the encoder for use in Embodiment 3;

Fig. 25 is a diagram illustrating another example of the decoder for

15    use in Embodiment 3;

Fig. 26 is a diagram illustrating still another example of the decoder for use in Embodiment 3;

Fig. 27 is a diagram illustrating a still further example of the decoder for use in Embodiment 3;

20    Fig. 28 is a diagram showing an example of an encoder/decoder combination according to Embodiment 2;

Fig. 29 is a system configuration illustrating an example of the communications system to which the first mode of working is applicable;

Fig. 30 is a system configuration illustrating an example of the

25    communications system according to Embodiment 2-1 of the second mode of working of the present invention;

Fig. 31 shows, by way of example, the relationships between the phase

corresponding to two values of piece of data and pseudo-carrier of a trigonometric function, Figs. 31(a), 31(b), 31(c) and 31(d) showing such relationships in the cases where the phase is 0, $\pi/2$, $\pi$ and $3\pi/2$, respectively;

Fig. 32-1 is a diagram showing, by way of example, the relationships of light source output, modulated output, filtering characteristic, filtered output and detected intensity at the receiving side in the case of a 0-phase modulated output in Embodiment 2-1;

Fig. 32-2 is a diagram showing, by way of example, the Fig. 32-1 relationships in the case of a $\pi/2$-phase modulated output;

Fig. 32-3 is a diagram showing, by way of example, the Fig. 32-1 relationships in the case of a $\pi$-phase modulated output;

Fig. 32-4 is a diagram showing, by way of example, the Fig. 32-1 relationships in the case of a $3\pi/2$-phase modulated output;

Fig. 33 is a diagram illustrating an example of a phase modulation part 130 in Fig. 30;

Fig. 34 is a diagram illustrating an example of an optical transmitter in Embodiment 2-2;

Fig. 35(a) is a diagram showing an example of an optical transmitter in Embodiment 2-3, and Fig. 35(b) a diagram showing an example of a modified form of a modulator 132 in Figs. 35(a);

Fig. 36(a) is a diagram showing signal points on the coordinates in QPSK, and Fig. 36(b) is a table showing the relationships of a data set, a coordinate point and a filter-selecting phase;

Fig. 37-1 is a diagram illustrating an example of an optical transmitter in the communications system according to Embodiment 2-4;

Fig. 37-2 is a diagram showing an example of an optical receiver for use in Embodiment 2-4;

Fig. 38(a) is a diagram showing signal points on the coordinates in QPSK, and Fig. 38(b) is a table showing the relationships of a data set, the filter-selecting phase and intensity to outputs from comparators 241 and 242;

Fig. 39 is a diagram illustrating another example of the optical transmitter for use in Embodiment 2-4;

Fig. 40 is a system configuration illustrating an example of a communications system according to Embodiment 2-5;

Fig. 41 shows examples of filtering characteristics in Embodiment 2-5, Figs. 41(a), 41(b), 41(c) and 41(d) showing the characteristics in the cases of where the phase is 0, $\pi/2$, $\pi$ and $3\pi/2$, respectively;

Fig. 42-1 is a diagram showing, by way of example, the relationships of the optical source output, a modulated output, a filtering characteristic, a filtered output at the receiving side and detected intensity to a 0-phase modulated output in Embodiment 2-5;

Fig. 42-2 is a diagram showing, by way of example, the Fig. 42-1 relationships in the case of the $\pi/2$-phase modulated output;

Fig. 42-3 is a diagram showing, by way of example, the Fig. 42-1 relationships in the case of the $\pi$-phase modulated output;

Fig. 42-4 is a diagram showing, by way of example, the Fig. 42-1 relationships in the case of the $3\pi/2$-phase modulated output;

Fig. 43(a) shows an example of an optical frequency characteristic function in the case where the chip number $L = 24$, $P = 4$, $n = 1$ and $S = 6$ in Embodiment 2-5, and Fig. 43(b) shows an example of the function in the case where $S = 3$ in the Fig. 43(a);

Fig. 44 shows, by way of example, the relationships of the chip number $L$, the phase shift amount $P$, a divisor $S$ and $Q$ and $n$ in Embodiment 2-5, Figs. 44(a), 44(b) and 44(c) showing the relationships in the cases where

P = 0, P = 1 and P = 2, respectively;

Fig. 45 is a diagram illustrating an example of an optical transmitter according to Embodiment 2-8;

Fig. 46 is a diagram showing, by way of example, optical chips of each of S-chip light source in Fig. 45;

Fig. 47 is a system configuration illustrating an example of a communications system according to Embodiment 2-9;

Fig. 48-1 is a diagram showing an example of an optical transmitter in a communications system according to Embodiment 2-11;

Fig. 48-2 is a diagram showing an example of an optical receiver in Embodiment 2-11;

Fig. 49 is diagram illustrating the functional configuration of an embodiment of reflective optical communication equipment according to the third mode of working of the present invention;

Figs. 50(a) and 50(b) are diagrams showing examples in which chip functions are used as the optical frequency characteristics in the third mode of working of the invention, respectively;

Fig. 51 is a diagram showing an example in which encoders 440M and 440S in Fig. 49 have chip functions;

Fig. 52 is a diagram showing a functional configuration of another embodiment of the reflective optical communication equipment according to the third mode of working of the invention;

Fig. 53 is a diagram illustrating the functional configuration of an example of this invention equipment in which transmitter and receiver circuits are provided in parallel;

Fig. 54 is a diagram showing an example of the chip function in the third mode of working of the invention;

Fig. 55 is a diagram illustrating the functional configuration of an example of optical communication equipment which is the communicating partner of the reflective optical communication equipment according to third mode of working of the invention;

5 Fig. 56 is a diagram illustrating the functional configuration of an example in which transmitter and receiver circuits each having a trigonometric function filtering characteristics are both provided;

Fig. 57 is a diagram showing the functional configuration of another example of an optical combiner in Fig. 53;

10 Fig. 58 is a diagram illustrating the functional configuration of another example in which the transmitter and receiver circuits are both provided in the third mode of working of the invention;

Fig. 59 is a diagram illustrating the functional configuration of an example in which the receiver circuit is connected in cascade to the output of 15 the transmitter circuit in Embodiment 3-5;

Fig. 60 is a diagram illustrating the function configuration of another example in which the receiver circuit is connected in cascade to the output of the transmitter circuit in Embodiment 3-5;

Fig. 61 is a diagram illustrating the function configuration of an 20 example in which the transmitter circuit is connected in cascade to the output of the receiver circuit in Embodiment 3-5; and

Fig. 62 is a diagram illustrating the function configuration of another example in which the transmitter circuit is connected in cascade to the output of the receiver circuit in Embodiment 3-5.

25 [BEST MODE FOR CARRYING OUT THE INVENTION]

[0016] A description will be given, with reference to the accompanying drawings, of embodiments of the present invention, and in the following

description, corresponding parts are identified by like reference numerals throughout the drawings and no description will be repeated.

FIRST MODE OF WORKING (Optical Code Division Multiplex)

The first mode of working of the present invention permits

5    implementation of optical code division multiplex, but is applicable as well to a single-data-sequence optical communication that does not involve optical code division multiplexing; however, the title of this section includes the "Optical Code Division Multiplex" in parentheses for ease in distinguishing between this and other modes of working of the invention.

10    A description will be given first of examples of transmitting- and receiving-side apparatuses to which the present invention is applicable.   Fig. 2(a) shows an example of the light transmitting-side apparatus to which the first mode of working is applied.   Sets of light sources $10_n$ and encoders $11_n$ are each connected via an optical fiber $14_n$ to a coupler 15, where n=1, 2, ...,

15    N (N being an integer equal to or greater than 2).   A data sequence $D_n$ is input to each encoder $11_n$, wherein it is encoded into an optical code signal, and the optical code signal is input via the optical fiber $14_n$ to the coupler 15, wherein it is combined with other optical code signals, and from which a combined optical code signal is output.   Shown in Fig. 2(a) is an example in

20    which the coupler 15 is disposed away from the encoders $11_1$, ..., $11_N$ at different distances.

[0017] Fig. 3(a) shows an example in which the encoders $11_1$, ..., $11_N$ and the coupler 15 are disposed at the same place and the light source 10 is provided in common to the encoders $11_1$, ..., $11_N$.   The arrangements of Figs. 2(a) and

25    3(b) may be used in combination.

In the light receiving-side apparatus, as depicted in Fig. 2(b), the multiplexed optical code signal input to a splitter 16 is split into N optical

signals, which are input via optical fibers $18_1, \ldots, 18_N$ to decoders $12_1, \ldots, 12_N$, respectively, by which the original data sequences $D_1, \ldots, D_N$ are demultiplexed and decoded. The splitter 16 may be placed away from the decoders $12_1, \ldots, 12_N$ at different distances. The splitter 16 and the decoders

5    $12_1, \ldots, 12_N$ may be disposed at the same place as shown in Fig. 3(b); it is also possible to employ a combination of the arrangements shown in Figs. 2(b) and 3(b).

[Embodiment 1-1]

Fig. 4 illustrates a single-channel communications system to which

10   Embodiment 1-1 of the first mode of working of is applicable. Embodiment 1-1 comprises, as is the case with the conventional optical communications system, a light source 10, an encoder 11, a decoder 12, and an optical transmission line (optical fiber) 13; furthermore, Embodiment 1-1 is provided with a dispersion compensator 17 that compensates for frequency-dependent

15   propagation delay time differences due to frequency dispersion of the optical transmission line by leveling off delay times of respective frequency components of the optical code signal between its transmission and reception. The optical frequency bandwidth over which the dispersion compensator 17 implements compensation is broader than at least the optical frequency

20   bandwidth of the optical code signal.

[0018] The light source 10 outputs an optical signal of an optical frequency width FSR corresponding to the code length FCL (a common multiple of FSRi described later on) at least in the optical frequency region (from optical frequencies Fst to Fla) for encoding by the encoder 11.

25   An optical signal 20 emitted from the light source 10 is encoded by the encoder 11 into an optical code signal in the optical frequency region. Unlike an encoder used in the conventional optical communications system

the encoder 11 for use in Embodiment 1-1 generates in the optical frequency region an optical code signal of the code length FCL which is equivalent to that of all encoding codes (code words) used in the optical communications system. The optical code signal in the above-mentioned optical frequency

5 region has such properties as mentioned below. The intensity of an n-th optical code signal is a function $Cn(f)$ of an optical frequency f (hereinafter referred to also as an encoding code); the function $Cn(f)$ takes a value from 0 to 1; the integration value of the function $Cn(f)$ for an interval of an arbitrary code length FCL in the optical frequency region from Fst to Fla for encoding

10 by the encoder 11 is a value obtained by dividing FCL by 2; and the optical frequency characteristic of the light transmittance through the encoder $11_n$ is, in general, a repetition of the same function $Cn(f)$ at intervals of the code length FCL in the optical frequency region from Fst to Fla for encoding by the encoder. And the following equations hold.

15 [0019] $Cn(f) = Cn(f+FCL)$     $n = 1, ..., N$     (1)

$$\int Cn(f) = FCL/2 \qquad (2)$$

In the following description an optical code signal whose optical frequency characteristic function of optical intensity is $Cn(f)$ will also be denoted by $Cn(f)$; that is, $Cn(f)$ represents an n-th encoding code, or n-th

20 optical code signal. The term "n-th (optical code signal)" corresponds to the term "n-th (optical code signal) in other modes of working of the invention, and (function or encoding code) $Cn(f)$" corresponds to "(optical frequency characteristic function or code) $Cn(f)$" in other modes of working of the invention.

25 [0020] The decoder 12 for decoding the optical code signal generated by the encoder 11 in Embodiment 1-1 is such that for the n-th optical code signal $Cn(f)$ the decoder $12_n$ continuously repeats generation of a function

(hereinafter referred to also as a decoding code) $Dn(f)$ whose one period is equal to the code length FCL in the optical frequency region for decoding: $Dn(f)$ is expressed by the following equation.

$$Dn(f) = Cn(f) - Cn'(f) \qquad (3)$$

where $Cn'(f)$ is a complementary value of the optical intensity value of the n-th encoded code $Cn(f)$, and a value of the function $Cn'(f)$ is the complementary value of the function $Cn(f)$; they bear the following relationship.

[0021] $Cn(f) + Cn'(f) = 1 \qquad (4)$

The scalar product of the value $Cn(f)$ of the n-th optical code signal at the optical frequency $f$ and the decoding code $Dn(f)$ from the decoder decoding the n-th optical code signal is integrated with respect to the optical frequency $f$ for a continuous optical frequency region corresponding to the code length FCL within each of the optical frequency region for encoding by the encoder and the optical frequency region for decoding by the decoder; the resulting value is a non-zero finite value FCL/4, which satisfies the following equation.

$$\int Cn(f) \cdot Dn(f)df = FCL/4 \qquad (5)$$

Incidentally, the integration of Eq. (5) is conducted over the optical frequency width FSR of the light source; in this example, FSR is just a natural-number multiple of the period FCL.

[0022] The scalar product of the n-th optical code signal $Cn(f)$ and the decoding code $Dm(f)$ from the decoder $12_n$ having decoded an m-th optical code signal $Cm(f)$ other than the n-th optical code signal $Cn(f)$, (where m=1, ..., N and except for m=n), is integrated over the continuous frequency region corresponding to the code length FCL within each of the optical frequency region for encoding by the encoder and the optical frequency region for

decoding by the decoder; the resulting value is zero, which satisfies the following equation.

$$\int Cn(f) \cdot Dm(f)df = 0 \qquad m \neq n, m = 1, ..., N \qquad (6)$$

As shown in Figs. 2 and 3, assume that the number of data sequences is a plural number N, that the first, ..., N-th data sequences are assigned first, ..., N-th encoding codes, respectively, and that the first, ..., N-th encoding codes are equal in their code length FCL. The optical frequency region for encoding by the encoder $11_n$ is set to be broader than the code length FCL of the optical code signal; the encoder $11_n$ generates and outputs the optical code signal $Cn(f)$ in accordance with the data of the n-th data sequence by encoding, in the optical frequency region, the optical signal input from the light source and having the optical frequency width which is at least the code length FCL. The length of the optical code signal $Cn(f)$ to be output is set at one code length FCL for each piece of data. For example, when the data is "1" (mark), the optical code signal $Cn(f)$ is output with one code length, and when the data is "0" (space), the optical code signal $Cn(f)$ is not output. Incidentally, the mark and the space correspond to the one and the other of two kinds of modulation unit signals.

[0023] As will be seen from Eqs. (3) and (5), the decoder $12_n$, which decodes the n-th data sequence from the optical signal having multiplexed thereinto optical code signals of the N data sequences, integrates the scalar products of the input optical code multiplexed signal and the n-th code signal $Cn(f)$ and its complementary optical code signal $Cn'(f)$, then detects the difference between the integrated values, and outputs "1" or "0" as decoded data, depending on whether the difference is equal to or greater than a predetermined value or smaller than the predetermined value.

As described above, in Embodiment 1-1, unlike in the prior art

example which uses a different wavelength period for each data sequence, the code length FCL that is equal to the optical frequency width over which all optical code signals are orthogonal to each other is identical, and the optical frequency characteristic of the transmittance of the encoder $11_n$ is such that

5    Cn(f) continuously repeats in the optical frequency region FSR for encoding by the encoder, and the optical frequency characteristic of the transmittance of the decoder $12_n$ is also such that Dn(f) continuously repeats in the optical frequency region Fst to Fla for decoding by the decoder; therefore, each optical code signal keeps the properties shown by Eqs. (1) and (2), and even if

10   the interval of integration is changed, the integrated value of the scalar product of each optical code signal in the decoder remains unchanged. Accordingly, in Embodiment 1-1 if the optical frequency width of the light source to be encoded is constant and the optical frequency width is included in each of the optical frequency region for encoding by the encoder and the

15   optical frequency region for decoding by the decoder, the optical code signal emitted from the encoder corresponding to the light source having its optical frequency changed is received by the decoder as an optical signal of the same intensity as that of the emitted optical signal, and no increase will be caused in the interference between the other optical code signals which do not

20   correspond to this decoder.   For example, as shown in Fig. 5(a), the optical frequency width of the output optical signal from the light source 10 is $f_{L1}$ to $f_{L2}$=FSR, and this optical frequency width is a natural-number multiple of the optical code length FCL over which almost codes are repeatedly generated (1 being chosen as the natural number in this embodiment); this optical

25   frequency width $f_{L1}$ to $f_{L2}$ is included in each of the optical frequency region for encoding by the encoder $11_n$ and the optical frequency region for decoding by the decoder $12_n$ as shown in Figs. 5(b) and (c).   Accordingly, even if the

optical frequency of the output light from the light source 10 drifts as indicated, for example, by the broken lines, as long as it stays within the optical frequency region for encoding and the optical frequency region for decoding, the optical code signal of the drifted optical frequency is decoded

5    by integrating the input multiplexed optical code signal and the decoding code Dn(f) over FSR (equal to the code length FCL in this example) corresponding to the optical frequency width of the light source; this integration and the relationships given by Eqs. (1) and (2) ensure generation of the same decoded signal as is obtainable without the optical frequency drift, and suppression of

10    an increase in interference.    Similarly, even if the optical frequency region for encoding and the optical frequency region for decoding drifts, decoding can be achieved with high accuracy.    The optical transmission bandwidth of the optical fiber for transmitting the combined optical code signal from the combiner 15 (see Figs. 2 and 3) needs only to be wider than the optical

15    frequency width FSR of the light source to such an extent as to fully accommodate optical frequency fluctuations of the light source.    The optical frequency region for encoding and the optical frequency region for decoding may also be the same as the above-mentioned optical transmission bandwidth. In other words, since codes are orthogonal to each other in the first mode of

20    working of the invention, the optical frequency width FSR of the light source may be equal to the code length FCL of every code, in which case the optical frequency width necessary for transmission over the optical fiber may be an optical frequency width that is the sum of the code length FCL and an optical frequency fluctuation of the light source.

25    [0024] The prior art disclosed in document 2 uses periodic codes of different code lengths of spreading codes, and requires, for canceling inter-code interference, an optical-band light source that is used to obtain optical signal

with a sine function over a sufficiently large number of periods. In Embodiment 1-1, however, such a broadband light source is not required, and the emitted light from the light source 10 needs only to have an optical frequency width (period width) corresponding to the code length FCL--this

5     permits reduction of the transmission frequency (wavelength) width accordingly, solving the problems of waveform deterioration by the influence of wavelength dispersion on the optical transmission line and limitations on the transmission bandwidth.

    Furthermore, the provision of the dispersion compensators 17 also

10     extenuates or minimizes the collapse of orthogonality between codes due to differences in their transmission distance.

[0025]

    As described above, in Embodiment 1-1 the optical frequency region for encoding by the encoder has an optical frequency width greater than the

15     code length FCL of the optical code signal, the optical code has the characteristics expressed by Eqs. (1) to (6), and the dispersion compensator 17 is disposed immediately before each decoder or behind each encoder as indicated by the broken line in Fig. 2(b) or 2(a); accordingly, even if the optical frequency of the output signal from the light source fluctuates within

20     the optical frequency range for encoding by the encoder irrespective of the distance between the encoder and the decoderand the optical frequency width of the output optical signal from the light source does not change, the output optical code signal from the encoder corresponding to the decoder is received by the latter as an optical code signal of the unchanged optical intensity and

25     no increase is caused in the interference by other optical code signals that do not correspond to this decoder--this allows the optical frequency of the output signal from the light source to deviate from a predetermined absolute

frequency, making it possible to avoid the necessity for calibration of the optical frequency of the output signal from the light source.

[Embodiment 1-2]

Embodiment 1-2 of the first mode of working of the invention is a specific operative example of Embodiment 1-1 and uses a trigonometric function as the encoding function C(f). In Embodiment 1-2, in the case of using the smallest possible and invariable value a (which is a positive integer) to generate r' codes, if the value a is taken as an integer value in the range of 1 to a value N/r' obtained by dividing the maximum number N of codes (the maximum number of local-office encoders) by r' and if r is taken as 0, 1, ..., r' − 1 that is the remainder of r', the n-th optical code $C_n(f)$ is used which is expressed by the following equation.

[0026] $$C_n(f) = (1 + \cos (2 \cdot \pi \cdot a \cdot f/FCL + r \cdot \pi/2)) /2 \qquad (7)$$

This optical code signal function $C_n(f)$ takes a value from 0 to 1, and the value of integration of the code signal function for an interval of an arbitrary code length FCL in the optical frequency region for encoding by the encoder $11_n$ is FSR/2; the optical frequency characteristic of the transmittance of the encoder $11_n$ is a repetition of the function $C_n(f)$ with a cycle of the code length FCL in the optical frequency region for encoding by the encoder and satisfies the relations of equations (1) and (2).

A description will be given below, by way of example, of the case where r' − 2, that is, the remainder of division of r by r' is 0 or 1 and a takes a value in the range of 1, ..., N/2.

[0027] In Fig. 6 there are shown examples of the optical code signal $C_n(f)$ in Embodiment 1-2. The abscissa represents the optical frequency normalized with the code length FCL and the ordinate represents optical intensity; Figs. 6(a), 6(b) and 6(c) correspond to values a = 1, 2 and 3, respectively, and the

broken and solid lines indicate optical code signals corresponding to $r = 0$ and $r = 1$, respectively. The optical code signal is one that single frequency optical signals corresponding to respective chips, except for $Cn(f) = 0$, vary in intensity in analog fashion in order of their arrangement unlike the spreading code consisting of single-frequency optical signals of which values are each "1" or "0" corresponding to one of chips as shown in the Fig. 1 prior-art example.

Used as the decoding code $Dn(f)$ of the decoder $12_n$ for decoding the n-th optical code signal $Cn(f)$ is expressed by the following equation.

[0028] $Dn(f) = (1 + \cos (2 \cdot \pi \cdot a \cdot f/FCL + r \cdot \pi/2)) - 1$       (8)

The scalar product of the n-th optical code signal $Cn(f)$ and the n-th decoding code $Dn(f)$ for decoding the n-th optical code signal is integrated over a continuous optical frequency region corresponding to the code length FCL included in each of the optical frequency region for encoding by the encoder and the optical frequency region for decoding by the decoder, the resulting value being a non-zero finite value FCL/4, and the scalar product of the n-th optical code signal $Cn(f)$ and a decoding code $Dm(f)$ of a decoder for decoding an m-th optical code signal other than the n-th one over a continuous frequency region corresponding to the code length FCL included in each of the optical frequency region for encoding by the encoder and the optical frequency region for decoding by the decoder, the resulting value being zero; these values satisfy Eqs. (5) and (6) in Embodiment 1-1.

[0029] Fig. 7 shows an example of the configuration of the encoder $11_n$ for use in Embodiment 1-2. A Mach-Zehnder interferometer is used, as the encoder $11_n$, which is made up of a pair of optical paths 41 and 42 of different optical path lengths and a pair of couplers 43 and 44 optically coupled thereto for coupling and splitting their optical inputs into two which are fed to the

optical paths. The light input to the one input port of the coupler 43 is output via two output ports to the optical paths 41 and 42. At the one output port of the coupler 43 is mainly provided light of an optical frequency component which is an integral multiple of the optical frequency dependent on the optical path difference between the optical paths 41 and 42, whereas at the other output port is provided mainly the other optical frequency component. This optical frequency selecting characteristic is a gentle one, not ON-OFF-wise; therefore, for example, in Fig. 6(a) the selected (normalized) optical frequency is f1 and an optical output of a cosine function is provided whose intensity is 1 at the selected optical frequency f1.

[0030] Accordingly, the n-th optical code signal Cn(f) given by Eq. (7) is provided as an output A from the one output port of the coupler 44. From the other output port is provided an complementary optical code signal Cn'(f) as an output B.

Fig. 8 shows an example of the configuration of the decoder $12_n$ for use in Embodiment 1-2. A Mach-Zehnder interferometer 55 is used which is made up of a pair of optical paths 51 of different optical path lengths and a pair of couplers 53 and 54 optically coupled thereto; a combined optical code signal is input to the Mach-Zehnder interferometer 55, which provides, as an output A at the one output port, the n-th optical code signal Cn(f) given by Eq. (7), and the optical intensity of the output is detected as an electrical signal by a detector 56a. As the other output B from the Mach-Zehnder interferometer 55 is provided an optical code signal Cn'(f) that is an complementary version of the n-th optical code signal Cn(f) given by Eq. (7), and the optical intensity of the output Cn'(f) is detected by a detector 56b as an electrical signal. The output A corresponds to the scalar product of the input combined optical code signal and the encoding code Cn(f), whereas the output B corresponds to the

scalar product of the input combined optical signal and an complementary code $(1 - Cn(f))$ of the encoding code $Cn(f)$ subtracted from 1. The output from the detector 56a is obtained by integrating the output A with respect to the optical frequency f of the light-source optical frequency width included in

5    the optical frequency region Fst to Fla for decoding, and the output from the detector 56b is obtained by integrating the output B with respect to f over the light-source optical frequency width FSR included in the optical frequency region Fst to Fla for decoding. An intensity difference detector 57 subtracts the optical intensity detected by the detector 56b from the optical intensity

10    detected by the detector 56a, providing the decoded output from the decoder $12_n$. For example, data "1" or "0" is output, depending on whether or not the output from the intensity difference detector 57 is equal to or greater than a threshold value.

[0031] As described above, since Embodiment 1-2 uses mutually orthogonal

15    optical code signals as in the case of Embodiment 1-1 unlike in the prior art example of document 2 using periodic codes of different code lengths for optical codes, the summation of scalar products of the different optical code signals over their code lengths is zero--this reduces inter-code interference as compared with the prior art example using the non-orthogonal periodic codes.

20    In Embodiment 1-2, if the optical frequency width of the optical output from the light source, which is encoded by the encoding code, is constant and if the optical frequency of the output light from the light source is allocated within each of the optical frequency region for encoding by the encoder and the optical frequency region for decoding by the decoder, there is

25    no influence of optical frequency fluctuations of the light source as is the case with Embodiment 1-1. Unlike the prior art using non-orthogonal periodic codes, this embodiment does not call for the use of a light source capable of

emitting light over a period large enough to ignore inter-code interference, that is, the optical frequency bandwidth of the output light from the light source need not be wide, in particular, and the transmission bandwidth needs only to be wider than the optical frequency width FSR of the light source to

5 such an extent as to accommodate optical frequency fluctuations of the light source; therefore, this embodiment permits suppression of waveform deterioration and limitations on the transmission bandwidth both attributable to wavelength dispersion on the transmission line.

[0032] Furthermore, in Embodiment 1-2, a $\pi/2$ phase shift of the optical code signal at the start position on the optical frequency axis, that is, changing r in

10 Eq. (7) to 0 or 1, as well as changing the frequency f, that is, a in Eq. (7) makes it possible to increase the number of encoding codes twice as large as in the case of changing only the period (a) for encoding.

[Modification of Embodiment 1-2]

15 Although in Embodiment 1-2 the optical code signal is output only when the data in the data sequence is "1" (mark), the optical code signal may also be output when the data is "0" (space). That is, the n-th optical code signal Cn(f) is output for the data "1" (mark) in the n-th data sequence and an complementary optical code signal Cn'(f) of the n-th optical code signal Cn(f)

20 is output for the data "0" (space). To perform this, the encoder $11_n$ is provided with a switch 45 which is disposed subsequent to the output-side coupler 44 as indicated by the broken lines in Fig. 7; the switch 45 is supplied with the outputs A and B and is controlled by the value of each piece of data of the data sequence Dn to provide the output A for the data "1" (mark) and

25 the output B for the data "0" (space), generating a non-return-to-zero optical modulation signal.

[0033] In this embodiment, Eqs. (9) and (10) hold for the mark.

$$\int Cn(f)\, Dn(f) = FCL/4 \qquad\qquad (9)$$

$$\int Cn(f)\, Dm(f) = 0 \qquad\qquad (10)$$

For the space, Equations (11) and (12) holds.

$$\int Cn'(f)\, Dn(f) = -\,FCL/4 \qquad\qquad (11)$$

5 $\qquad\int Cn'(f)\, Dm(f) = 0 \qquad\qquad (12)$

In this embodiment, too, integration is conducted over the optical frequency width FSR of the light source, but the width FSR is equal to the code repetition optical frequency width FCL.

[0034] Accordingly, the optical intensity difference detector 57 outputs a

10 signal composed of mark and space codes and hence twice (3 dB) larger than in the above-described embodiment in which the intensity difference detector 57 is supplied with only the "mark" optical signal and provides an output that goes to PCL/4 for the mark and to 0 for the space. This increases the signal-to-noise ratio by 3 dB and hence permits reduction of the code length

15 FCL accordingly, thereby lessening the influence of wavelength dispersion of the transmission line. Incidentally, the switch 45 may also be disposed at the stage preceding the input-side coupler 43, as indicated by the broken line in Fig. 7, in which case the input light is input to either one of two input ports of the coupler 42, depending on the data Dn is mark or space, and the output

20 light is derived from only one of the output ports of the output-side coupler 41. Also the signs of the mark ("1") and the space ("0") may be exchanged. In other words, the correspondence between the mark ("1") and the space ("0") and between the optical code signals Cn(f) and Cn'(f) may be arbitrary.

[0035] The encoder $11_n$ may also be configured as depicted in Fig. 9. As is

25 the case with an LN modulator, there are formed on a planar lightwave circuit substrate 46 formed of a material which has an electrooptic effect, such as $LiNbO_3$ crystal: two waveguides 47 and 48; couplers 43 and 44 formed by

bringing the waveguides close to each other at locations adjacent their opposite end portions; and a pair of electrodes 49 for applying an electric field to at least either one of two optical paths 41 and 42 formed by the waveguides between the couplers 43 and 44 so as to provide a propagation delay

5     difference between the two optical paths 42 and 41 by birefringence shift that is caused under the electric field by the electrooptic effect.   The voltage that is applied to the optical path (waveguide) by the pair of electrodes 49 is adjusted such that the encoder $11_n$ selects and outputs the optical frequency (wavelength) signal which satisfies Eq. (7) corresponding to each optical code

10     signal $Cn(f)$.

[0036] The decoder $12_n$ can similarly be formed as a Mach-Zehnder interferometer or filter by forming optical paths 51, 52 and the couplers 53, 54 on the planar lightwave circuit substrate as parenthesized in Fig. 9.   In this instance, the voltage to be applied to the electrodes 49 is so adjusted as to

15     satisfy Eq. (8).

With the Fig. 9 configuration, it is possible to change the encoding code $Cn(f)$ or decoding code $Dn(f)$ by changing the voltage which is applied to the electrodes 49--this eliminates the need for forming a different encoder-decoder pair for each encoding code, and hence permits reduction of

20     the device manufacturing costs.

Further, as depicted in Fig. 9, a pair of encoders $11_n$ and $11_m$ ($n \neq m$) are integrated on the same planar lightwave circuit substrate 46 whose temperature varies uniformly throughout it, and these encoders $11_n$ and $11_m$ generate n- and m-th optical code signals $Cn(f)$ $Cm(f)$ which are common in

25     the value a but different in the value r in Eq. (7), respectively.   Since the two optical code signals $Cn(f)$ and $Cm(f)$ are identical in their optical frequency characteristic and have a phase number difference of $\pi/2$, unsimultaneous

occurrence of temperature variations in the encoders $11_n$ and $11_m$ for encoding the optical code signals, respectively, changes their refractive indexes and optical path lengths and hence causes their optical frequency for filtering to drift, resulting in deterioration of the value of cross-correlation between the optical code signals Cn(f) and Cm(f).   With the Fig. 9 configuration, however, it is possible to suppress the deterioration of the correlation between the optical code signals by temperature variations since the encoders $11_n$ and $11_m$ are mounted on the common planar lightwave circuit substrate which undergoes uniform temperature variations.

[Embodiment 1-3]

In Embodiment 1-3 of the first mode of working of the invention, the intensity of the chip, which is each optical frequency component of the optical code signal, goes to a 1 or 0.   The configuration of the communications system to which Embodiment 1-3 is applicable may be the same as the Fig. 4 configuration.

[0037] The optical code signals, i.e. first to N-th optical code signals, generated by the encoder $11_n$ in Embodiment 1-3 have the same code length FCL and are orthogonal to each other as in Embodiments 1-1 and 1-2; and they have such properties as mentioned below.   The numbers of chips "1" and chips "-1" in a string of chips of the code length FCL arbitrarily taken out of a continuously repeated concatenation of the encoding code Cn(f) of the code length FCL are equal (the same number), and the numbers of chips which simultaneously go to "1s" and "-1s", respectively, at the same positions in strings of chips of the code length FCL arbitrarily taken out of different concatenations of different encoding codes are equal to each other.   In the case of a code composed of such chips, the code length is a mere abstract number with no unit.   Accordingly, it can be said in the above-described

embodiments, too, that the code length is the optical frequency width FCL over which all codes repeat.

[0038] Such a code can be generated by use of the Hadamard code. Fig. 10(a) shows a first-order Hadamard matrix $H_1$, Fig. 10(b) a second-order Hadamard matrix $H_2$, and Fig. 10(c) a recurrence formula $H_n$ of the Hadamard matrix. A Hadamard code word is a selected row from the Hadamard matrix, except the first row, and its 0 and 1 are substituted with 1 and -1, respectively. In the second-order Hadamard matrix, the Hadamard code is composed of a code 2 [0101] in the second row of the matrix, a code 3 [0011] in the third row, and a code 4 [0110] in the fourth row. Continuously repeated concatenations of these codes 2 to 4 are [...0101010101...], [...001100110011...], and [...011001100110...], respectively. In this case, since the concatenation of code 3 and the concatenation of code 4 have their 1-chip codes shifted from each other, they constitute identical encoding codes, and Embodiment 1-3 uses only one of them.

[0039] In the encoder $11_n$, consecutive optical frequencies are sequentially assigned to respective chips of such a concatenated code in the order of their arrangement, and those optical frequency components of the input light corresponding to the chips "1" are selected, that is, encoded. The selection optical frequency components of the encoder corresponding to the concatenation of the code $C_1 = (0101)$ are such as depicted in Fig. 11(a), and the selection optical frequency components of the encoder corresponding to the concatenation of the code $C_2 = (0011)$ are such as depicted in Fig. 11(b).

The encoder $11_n$ is configured to receive from the light source a light input of an optical frequency width $F_w$ equal to or a little larger than a natural-number multiple of the code length FCL and hence filter the optical frequency signal (component) corresponding to each chip of the

concatenation of the encoding coder Cn(f) and output the filtered optical
frequency signals as the optical code signal Cn(f) corresponding to the N-th
data sequence, or output the optical code signal Cn(f) of the N-th data
sequence in which the optical frequency signal (component) corresponding to

5      each chip is ON for the data "1" of the N-th data sequence and OFF for the
data "0".   The thus encoded optical code signals each possess the
above-mentioned properties of the chip string arbitrarily taken out from the
concatenation of codes, maintaining orthogonality between different optical
code signals.

10     [0040] The decoder $12_n$ also filters the optical frequency component (signal)
of the input light corresponding to the concatenated code as is the case with
the encoder $11_n$, and performs decoding over the frequency width
corresponding to at least the code length FCL.   Fig. 12 shows an example of
the configuration of the decoder $12_n$.   The multiplexed optical code signal is

15     split by a splitter 61 into two for application to filters 62a and 62b; the filter
62a filters the optical frequency signals of the same order of output from the
corresponding encoder $11_n$, that is, the optical frequency signals
corresponding to the same chips as in the output from the corresponding
encoder, and the filter 62b filters the optical frequency signals corresponding

20     to complementary versions of the encoded codes of the corresponding
encoders $11_n$, that is, the optical frequency signals corresponding to chips not
selected by the encoder $11_n$.   The optical intensity of the optical frequency
signal filtered or selected by the filter 62a and the optical intensity of the
optical frequency signal filtered or selected by the filter 62b are detected by

25     detectors 63a and 63b, respectively, and the output from the detector 63b is
subtracted by an intensity difference detector 64 from the output from the
detector 63a.   In this way, optical code signals corresponding to consecutive

chips forming at least the encoded code are decoded from the output light of the encoder $11_n$.

[0041] Referring next to Fig. 13, a description will be given of how Embodiment 1-3 excludes the influence of the source frequency drift. Fig. 13(a) shows the state in which there is no source frequency drift . The optical signal 20 of the source frequency width $F_W$ corresponding to or a little larger than the code length FCL is output from the light source, and those optical frequency components of the optical frequency signal 20 corresponding to the chips "1" are filtered (encoded) by the encoder $11_n$ in its encoding optical frequency region 31, by which an optical code signal 21 is generated. The decoder $12_n$ filters the input optical code signal 21 in its decoding optical frequency region 32 to provide a decoded optical signal 22.

[0042] When the source frequency drifts by $\Delta F_1$ as shown in Fig. 13(b), the optical signal 20 input to the encoder $11_n$ is shifted by $\Delta F_1$ in the same direction as that of the source frequency drift in the encoding frequency region 31, in which the input optical signal is encoded into the optical code signal 21, whereas in the decoder $12_n$ the input multiplexed optical signal 21 is also shifted by $\Delta F_1$ in the same direction as that of the source frequency drift in the decoding frequency region, in which the input signal is decoded into an output optical signal 22.

Similarly, even when the source frequency drift is $\Delta F_2$ larger than in the above as shown in Fig. 13(c), if the drifted optical signal 20 remains within the encoding frequency region 31 and within the decoding frequency region 32, the optical signal is shifted by $\Delta F_2$ in both regions and encoded and decoded, respectively; in either case, the optical code signal 21 held orthogonal to a different optical code signal as described previously.

[0043] Incidentally, since it is absolutely impossible for the optical signal to

be negative in intensity, it can easily be understood that replacing the chip

value "-1" by "0", the value of definite integrals of scalar products of the code

$C_n(f)$ and the decoding code $C_n(f)$ and its complementary code $(1 - C_n(f))$

with respect to the optical frequency f over the source frequency $F_w$,

5      respectively, bear the relationship expressed by the following Equation (13).

$$\int C_n(f) \cdot C_n(f) \, df > \int C_n(f) \cdot (1 - C_n(f)) \, df \qquad (13)$$

[Examples of Filters of Encoder/Decoder in Embodiment 1-3]

A description will be given below of examples of the filter for use in

the encoder/decoder for continuously encoding/decoding optical signals in

10     Embodiment 1-3.    Fig. 14 depicts an example of the filter.    Multiple

variable couplers 71, whose coupling factors can be set arbitrarily, are

connected in cascade via delay lines 72, and optical outputs from those output

ports of the couplers 71 to which the delay lines 72 are not connected are

provided via phase shifters 73 to a combining coupler 74, from which a

15     filtered optical output signal is derived.    The optical frequency for filtering

by this filter may a continuous repetition of an arbitrary sequence of optical

frequencies with a predetermined period (FCL) as disclosed, for example, in

Sasayama et al., "Photonic FDM Multichannel Selector Using Coherent

Optical Transversal Filter," Journal of Lightwave Technology, Vol. 12, No. 4,

20     1994, pp. 664-669.    That is, it is possible to use the encoding light filtering

frequency characteristic function $C_n(f)$ that optical frequencies corresponding

to respective chips "1" of the encoding code are continuously repeated with a

period of the code length FCL.

[0044] In Embodiment 1-3, since the optical code signal can be sent over the

25     optical frequency width corresponding to the encoding code length FCL

without concatenation, the required source optical frequency width can be

made smaller than in the case of the conventional method using the sine

function for encoding--this lessens the influence of wavelength dispersion on the transmission line.   Moreover, as is the case with Embodiment 1-1, the provision of the dispersion compensator 17 also extenuates the collapse of orthogonality between optical code signals due to differences in their

5    transmission distance.

As described above, in Embodiment 1-3, even if the source frequency shifts, as long as it remains within the optical frequency range for encoding by the encoder, and the optical input has at least the frequency width corresponding to the code length FCL of the encoding code, the optical code

10   signal from the encoder is received by the corresponding decoder at the same input intensity as the source frequency does not shift and is held orthogonal to optical inputs from other encoders noncorresponding to the decoder to thereby cancel the inter-code interference.   This permits implementation of an optical communications system free from the necessity for calibrating the source

15   frequency.

[Modified Decoder in Embodiment 1-3]

Fig. 15 shows a modified form of the decoder $12_n$ in Embodiment 1-3. A filter 62 provides the output A by filtering the optical frequency signals corresponding to the optical frequency selective characteristics of the encoder

20   $11_n$, that is, the optical frequency signals corresponding to the chips "1", and it provides the output B by filtering the optical frequency signals corresponding to complementary characteristics of the optical frequency selective characteristics of the encoder $11_n$, that is, the optical frequency signals corresponding to the chips unfiltered by the encoder $11_n$.   The outputs A and

25   B from the filter 62 are input to detectors 63a and 63b, respectively, for detecting their optical intensity, and the detected are applied to an intensity difference detector 64, which subtracts the output of the detector 63b from the

output of the detector 63a and provides the subtracted output. The output from the intensity difference detector 64 is branched for input as well to a controller 65, and in accordance with the input thereto the controller 65 shifts the filtering optical frequency of the filter 62 to maximize the output from the

5    intensity.

[0045] Fig. 16 illustrates a specific operative example of the filter 62 in Fig. 15. The filter 62 can be used also as an encoder. The illustrated filter 62 is formed by a multistage Mach-Zehnder interferometer comprised of: two optical paths 76a and 76b having their optical path lengths made different by

10    the insertion of delay lines 75 in one of the two optical paths; couplers 77 interconnected via the two optical paths 76a and 76b, for combining and splitting light from the optical paths; and phase shifters 73 inserted in one of the two optical paths 76a and 76b. The filter periodically selects optical frequencies. The optical frequency for filtering (filtering optical frequency

15    characteristic function) by the filter 62 may be a continuous repetition of an arbitrary sequence of optical frequencies with the predetermined period (FCL) as disclosed, for example, in Jinguji et al., "Synthesis of Coherent Two-Port Lattice Form Optical Delay-Line Circuit," Journal of Lightwave Technology, Vol. 13, No. 1, 1995, pp. 73-82. The filter 62 provides the output A and the

20    output B from the one and the other of two output ports of the last-stage coupler 77, respectively. When the filter is used as the encoder, for example, only the output A is provided as the filtered optical code signal from one of the two output ports.

[0046] In the filter of Fig. 16 both port outputs of the coupler of each stage

25    are fed to the next stage and the output A from the last-stage coupler 77 is one-half the input, whereas in the filter of Fig. 14 the output decreases by 1/number of couplers 71; accordingly, when used as an encoder, the filter

shown in Fig. 16 is lower in the splitting loss by couplers.

As described above, the filter 62 in Fig. 15 may be configured as shown in Fig. 16 or 14, and its filtering optical frequency can be shifted simply by adjusting one or more of the delay of the delay line, the shift amount of the phase shifter and the splitting ratio of the variable coupler. The maximum value of adjustment in this case needs only to be equal to the code length FCL since the optical frequency width required for orthogonality of codes is FCL in this example.

[0047] Fig. 17 shows an example of the filter 62 whose filtering optical frequency is adjustable. This example uses delay lines 75' whose delay amounts can be varied by an electrode or heater for causing a refractive index change through utilization of a change in the birefringent index by the application of an electric field as described previously with reference to Fig. 9 or through utilization of the thermooptic effect by temperature--this permits adjustment of the optical path length difference between the optical paths 76a and 76b. The filter is formed by a multistage Mach-Zehnder interferometer comprised of the optical paths 76a and 76b, two couplers 77 for coupling and splitting light from the two optical paths, and the variable delay lines 75' inserted in the one optical path. This filter varies the delay amount of the variable delay line 75' to shift the optical frequency to be selected by each Mach-Zehnder interferometer forming the filter, thereby changing the encoding code of the encoder $11_n$ and the decoding code of the decoder and shifting the optical frequencies of the encoded and decoded codes.

[0048] The delay line of the filter for use in the encoder $11_n$ or decoder $12_n$, whose delay amount is variable and adjustable, that is, a variable delay line is such as shown in Fig. 18, in which multiple delay lines $75_1$ to $75_p$ of different delay amounts (the delay amount of the delay line $75_p$ being zero) are

connected in parallel between two switches or couplers 77 and 78 for selectively connecting multiple optical paths to a single optical path. An optical signal is output via one delay line $75_p$ (where p = 1, ..., P) having selected the optical input. The use of switches in this case excludes the

5 possibility of incurring an optical loss by the splitting loss of the couplers. Since a desired delay is provided by selectively switching multiple delay lines of different delay times, instead of utilizing the thermooptic effect or a birefringent index change by the application of an electric field, it is possible to cause a larger change in the delay.

10 [0049] Fig. 19 shows another example of such a delay line configuration, which is formed by a multistage connection of an optical path provided with a delay line 81, an optical path with no delay line and a switch 82 for switching between these delay lines, and in which the amount of delay on the optical input is changed by selectively switching the switches 82 between the two

15 kinds of delay lines.

The delay lines 81 may preferably be different in delay amount. The delay of the optical input is adjusted by selectively changing the combination of delay lines 81 for the passage therethrough of the optical input. Though smaller in the number of delay lines used, the illustrated delay structure

20 produces the same effect as is obtainable with the Fig. 18 example.

[0050] Referring next to Fig. 20, it will be described below that Embodiment 1-3 permits excellent decoding irrespective of a drift in the optical frequency for encoding by the encoder $11_n$. In Fig. 20 the parts corresponding to those in Fig. 13 are identified by the same reference numerals as in the latter. Fig.

25 20(a) shows the state in which there is no drift in the optical frequency for encoding by the encoder (optical filtering frequency characteristics), and the encoder and decoder operate in the same manner as in the case of Fig. 13(a).

When the optical frequency for encoding by the encoder drifts $\Delta F_1$ as depicted in Fig. 20(b), the optical input is encoded by filtering into an optical code signal 21'. When the optical frequency for encoding undergoes a relatively large drift $\Delta F_1$ as shown in Fig.20(c), the optical input is encoded by filtering into an optical code signal 21".

[0051] Either of the optical code signals 21' and 21" has the code length FCL; accordingly, the optical code signals 21' and 21" have the same properties as does the string of consecutive chips extracted from the concatenated code over the source frequency FSR (denoted by $F_W$ in Fig. 20) as described previously. Therefore, the decoder $12_n$ selects respective optical frequency components of the optical code signals 21' and 22", and outputs decoded signals 22' and 22" as shown in Figs. 20(b) and (c), respectively; thus, this embodiment ensures satisfactory decoding. When the optical frequency for decoding drifts, the decoder $12_n$ described above with reference to Fig. 15 is used to shift the optical frequency for decoding, by which satisfactory decoding can be achieved.

[0052] As described above, according to Embodiment 1-3, even if one or both of the source frequency, the optical frequency region for encoding 31 and the frequency region for decoding 32 drift, as long as the optical frequency width of the optical signal from the light source lies within the regions 31 and 32 (the region 32 including the shift-controlled region), no degradation is caused in the optical intensity of the input to the decoder and the orthogonality to other optical code signals is also retained--this enables the decoder to perform satisfactory decoding.

[Modifications of Encoder and Decoder of Embodiment 1-3]

Fig. 21 illustrates another example of the filter for use in the encoder $11_n$ and decoder $12_n$ of Embodiment 1-3. The optical input is fed to a filter

84; the filter 84 outputs optical frequency signals of respective chips forming the encoding code to different ports, and outputs to the same port those optical frequency signals which are spaced apart the optical frequency corresponding to the code length.   For example, assuming that the encoded code is

5    composed of four chips and that optical frequencies $F_1$, $F_2$, $F_3$ and $F_4$ are sequentially assigned to the chips in the order of arrangement, an optical signal of an optical frequency $F_1$ + qFCL (where q = 0, 1, 2, ...) is output to a port 1, and optical signals of optical frequencies $F_2$ + qFCL, $F_3$ + qFCL and $F_4$ + qFCL are output to ports 2, 3 and 4, respectively.   As the filter that

10   repeatedly outputs optical signals of consecutive frequencies to different ports as mentioned above, an AWG (Arrayed Waveguide Graiting) can be used which is of the type that the product of the number of optical signals to be split and their frequency interval and the free space range of the optical signals to be output to the same port are equal to the code length FCL.

15   Incidentally, while the Free Space Range defined for AWG is abbreviated as FSR, it is not the optical frequency width FSR used herein but, by the definition of FSR in this specification, it is represented as C/FCL (C: light speed).

[0053] The ports, at which the optical frequency signals corresponding to the

20   selection frequency components, that is, chips "1" of the encoding code, of the filter 84 are provided, are connected via optical paths 85 to a coupler or combiner 86a, and the output from the coupler or combiner 86a is provided as the output A.   The ports, at which the optical frequency signals corresponding to the chips "-1" of the encoding code, that is, unselected

25   optical frequency signals, are provided, are connected via optical paths 87 to a coupler or combiner 86b, and the output from the coupler or combiner 86b is provided as the output B.   The Fig. 21 example shows the path connection

for the encoding code $C_2 = (0011)$ depicted in Fig. 11(b). The ports 1 and 2 for $F_1$ + qFCL and $F_2$ + qFCL are connected via the optical paths 87 to the combiner 86b, whereas the ports 3 and 4 for $F_3$ + qFCL and $F_4$ + qFCL are connected via the optical paths 85 to the combiner 86a.

5    [0054] It will easily be understood that the filter of the Fig. 21 configuration can be used as a filter for either of the encoder $11_n$ and the decoder $12_n$.

In the encoder $11_n$ either one of the couplers or combiners 86a and 86b and the optical paths 85 or 87 corresponding thereto can be omitted. Rather than the couplers or combiners 86a and 86b which split or couple light 

10    irrespective of its optical frequency and hence causes a splitting loss, it is preferable to use arrayed waveguide grating as combiners not as filters in the above example since the optical loss by the splitting loss can be reduced. This filter is smaller in the number of parts than the filter of Fig. 14, and hence has the advantage of low optical loss.

15    [0055] The encoder $11_n$ may be configured as shown in Fig. 22. The same filter as that 84 in Fig. 21 is used, and its ports are connected to a combiner 92 via switches $91_1$, ..., $91_E$ (where E is the number of chips forming the encoding code) which selectively permit or inhibit the passage therethrough of light to optical paths $89_1$, ..., $89_E$. Those of the switches $91_1$, ..., $91_E$

20    which correspond to the chips "1" of the encoding code are turned ON and those corresponding to the chips "-1" are turned OFF.

Fig. 23 shows an example of the decoder formed using the filter 84. The decoder is provided with switches $93_1$, ..., $93_E$ through which the optical paths $89_1$, ..., $89_E$ connected to respective ports of the filter 84 are selectively

25    connected to either one of combiners 92a and 92b, and those of the switches $93_1$, ..., $93_E$ which corresponds to chips "1" are connected the combiner 92a, whereas those corresponding to the chips "-1" are connected to the combiner

92b.    The outputs from the combiners 92a and 92b are applied to detectors 63a and 63b, respectively; the subsequent stage is the same as shown in Figs. 12 and 15.

[0056] The configurations of Figs. 22 and 23 can be adapted to
5    generate/decode an arbitrary optical coded/decoded signal with one encoder/decoder.

Fig. 24 illustrates an other example of the encoder using the filter 84. The optical input is fed via an optical circulator 94 to the filter 84; the optical paths $89_1$, ..., $89_E$ connected at one end to the respective ports of the filter 84
10    are connected at the other end to selective reflectors $95_1$, ..., $95_E$ capable of selectively reflecting light, and the light reflected by the reflectors $95_1$, ..., $95_E$ back to and combined by the filter 84, from which the combined light is output via the optical circulator 94 separately of the optical input.   Those of the selective reflectors $95_1$, ..., $95_E$ which correspond to the chips "1" of the
15    encoding code of the encoder are set for reflection, whereas those reflectors corresponding to the chips "-1" are set for no-reflection.

[0057] Another example of the decoder using the filter 84 is depicted in Fig. 25, in which the parts corresponding to those in Figs. 23 and 24 are identified by the same reference numerals as those in the latter.   Connected to the
20    optical paths $89_1$, ..., $89_E$ at one end thereof are pass/reflect switches $96_1$, ..., $96_E$ that can be set to transmit therethrough light or reflect it off.   The light allowed to pass through the pass/reflect switches $96_1$, ..., $96_E$ is combined by the combiner 92a and then fed to the detector 63a.   The light reflected off the pass/reflect switches $96_1$, ..., $96_E$ is combined by the filter 84, from which the
25    combined output is provided via the circulator 94 to the detector 63b.   Those of the pass/reflect switches 961, ..., 96E which correspond to the chips "1" of the encoding code are set for transmission, whereas those corresponding to

the chips "-1" are set for reflection. With the illustrated configuration, it is possible to decrease the number of combiners used in the decoder of Fig. 23 by one.

[0058] It is desirable to insert attenuators $90_1$, ..., $90_E$ each in one of the

5 optical paths $89_1$, ..., $89_E$ as indicated by the broken lines in Figs. 21 to 25 to provide an optical loss corresponding to the optical intensity ratio of the output from the filter 48 for each optical path, thereby leveling off an intensity difference of several dBs for each optical path which is likely to be caused by the arrayed waveguide grating AWG. This permits reduction of noise

10 resulting from an intensity variation for each optical frequency.

Fig. 26 illustrates still another example of the decoder using the filter 84. This example is shown as being applied to the decoding of optical code signals of the code words $C_1 = (0101)$ and $C_2 = (1100)$ shown in Figs. 11(a) and (b). The intensity outputs of optical frequency signals corresponding to

15 the chips "1" of the optical code signal in the detectors $63_1$, ..., $63_4$ are applied as positive outputs to intensity difference detectors, and the intensity outputs of the optical frequency signals corresponding to the chips "-1" are applied as negative outputs to the intensity difference detectors. The outputs from detectors $63_1$ and $63_3$ are applied to positive input terminals of the intensity

20 difference detector $64_n$ for the code word $C_1$, and the outputs from the detectors $63_2$ and $63_4$ are applied to negative input terminals of the difference detector $64_n$, which conducts an addition and a subtraction using the inputs to the positive and negative input terminals as additive and subtractive inputs, respectively, and provides the result of addition and as a decoded signal

25 output. The outputs from detectors $63_1$ and $63_2$ are applied to positive input terminals of the intensity difference detector $64_m$ for the code word $C_2$, and the outputs from the detectors $63_3$ and $63_4$ are applied to negative input

terminals of the difference detector $64_m$, which adds and subtracts them, providing a decoded signal output. Alternatively, the intensity difference detector 64 may also be adapted to calculate the sum of the outputs from the detectors corresponding to the chips "1" of the encoded code and the sum of

5  the detector outputs corresponding to the chips "-1" and subtract the latter from the former to provide the decoded signal output.

[0059] This configuration eliminates the need for splitting light for each encoding code (code word) for decoding, and hence permits reduction of optical loss accordingly. As described previously with reference to Fig. 15,

10  it is preferable in this instance, too, to control the filtering optical frequency of the filter 84 in such a manner as to maximize one decoded signal output.

Fig. 27 illustrates another example of the decoder using the filter 84. This example uses electrical delay means as the dispersion compensator. The outputs from the detectors $63_1$, ..., $63_4$ connected to the output paths of

15  the filter 84 are applied to a switch 97, which outputs code words added with positive and negative signs, and the detected outputs corresponding to respective chips of the encoded code are each electrically delayed by delay means 98 to equalize different arrival times of chips due to different delay times of respective optical frequencies during transmission, and the

20  delay-equalized detector outputs are added by the intensity difference detectors $64_n$ and $64_m$, respectively. This example implements a dispersion compensation of electrical signals, and hence lessens the burden of dispersion compensation of optical signal. By changing the setting for the switching operation of the switch 97, arbitrary encoded codes can be decoded. The

25  delay means 98 can be dispensed with.

[Other Modifications]

In the encoder $11_n$ a filter of the type providing an output A and an

complementary output B is used, and the switch 45 is connected to the output

side of the filter as indicated by the broken line in Fig. 16, and the switch 45

is controlled by a data sequence $D_n$ to provide the output A or B, depending

upon whether the data is the mark ("1") or space ("-1"); thus, the output is

5    provided as a non-return-to-zero signal.   In this instance, too, the switch 45

may be connected to the input side of the filter as described previously in

respect of Fig. 9.    Further, as in the case of adding the broken-line part in Fig.

7, a gain of 3 dB can be obtained.

[0060] As depicted in Fig. 28, a pair of encoder $11_n$ and decoder $12_m$ is

10    integrated on a planar lightwave circuit substrate 46 common to them.    The

n-th encoding code of the encoder $11_n$ and the m-th decoding code of the

decoder $12_m$ are common in the value a but different in the value r in Eq. (7).

The pair of encoder $11_n$ and decoder $12_m$ is placed at one end of a

communications system and a pair of encoder $11_m$ and decoder $12_n$ is placed

15    at the other end of the communications system.    In accordance with the

optical frequency of the optical code signal that is received by the decoder

$12_m$ of the one communications system, the temperature of the planar

lightwave circuit substrate carrying the decoder is adjusted as described

previously with reference to Fig. 15.    Since the encoder $11_n$ and the decoder

20    $12_m$ are integrated on the same planar lightwave circuit substrate which

undergoes a uniform temperature change throughout it, the optical frequencies

for filtering by the filters of the encoder $11_n$ and the decoder $12_m$ can be

controlled synchronously by the above temperature adjustment.    Accordingly,

this temperature adjustment makes it possible to lower the cross-correlation

25    between the optical frequency of the n-th optical code signal from the encoder

$11_n$ on the temperature-adjusted side, in this example, and the optical

frequency of the m-th decoding code of the decoder on the

non-temperature-adjusted side.    As in the case of Fig. 9 wherein the two

encoders $11_n$ and $11_m$ are formed on the same circuit substrate 46, the

encoders, which encode optical code signals the cross-correlation between

which degrades upon occurrence of individual temperature changes of the

5     encoders, are integrated on the same planar lightwave circuit substrate which

undergoes a uniform temperature change throughout it--this suppresses

deterioration of the cross-correlation.    The temperature of the planar

lightwave circuit substrate may be controlled through utilization of the

intensity of the light transmitted through the encoder.    In the case of using

10    two encoders each of which outputs an optical signal of an optical

intensity-frequency characteristic function $Cm(f)$ for the one value of binary

data and an optical signal of an optical intensity-frequency characteristic

function $(1-Cm(f))$ for the other value, the above-mentioned temperature

adjustment may preferably be made in accordance with the intensity

15    difference between the transmitted light outputs from the both encoders.

Furthermore, in the case of using the Fig. 9 structure, the maximum number

of system users decreases by half since each user is assigned two encoding

codes.    With the Fig. 28 structure, however, because of the combined use of

the decoder and the encoder, the maximum number of system users does not

20    decrease by half despite the use of the encoding scheme free from interference

by reflected light.    Though described above as using the same encoded code

as that used in Embodiment 1-2, this embodiment can similarly be applied to

the Hadamard optical code signals shifted one chip apart in Embodiment 1-3

since the one-chip shift can be suppressed.

25    [0061] Now consider such an optical communications system as shown in Fig.

29, which comprises: a plurality of local office devices; a plurality of optical

fibers $13_A$, $13_B$ and $13_C$ for transmitting therethrough signals from the local

office devices; a line concentrating circuit 99 for concentrating the signals from the optical fibers $13_A$, $13_B$ and $13_C$ into a single optical fiber 13; and a central office device Cst that receives the concentrated optical signal from the concentrating circuit 99 via the single optical fiber 13.   In such a system

5    configuration encoders of the respective local offices are disposed in the concentrating circuit 99 for concentrating the optical signals from the multiple optical fibers into the single fiber 13.   That is, this is the same configuration as that depicted in Fig. 3(a).   Since the optical signals from all the local office devices can thus be subjected to the same wavelength dispersion

10   irrespective of the distances between the local office devices and the central office device, the same dispersion compensation can be implemented for the optical code signals from the encoders of the respective local office devices.   Accordingly, dispersion compensation can be provided for the optical code signals from all the encoders by a single dispersion compensator which makes

15   compensation to level off the optical frequency-dependent delay of the optical fiber 13 connecting the concentrating circuit 99 to the central office device. Because of the centralized disposition of the encoders, the encoding optical frequencies of all the encoders can easily be adjusted at one location.

[0062] In the above description, the optical signal from the light source 10 is

20   input to the encoder11 and is added with the optical frequency characteristic $Cn(f)$ according to the optical filtering frequency characteristic corresponding to the encoding code $Cn(f)$ of the encoder 11, and then the optical signal is turned ON and OFF according to the mark and the space to generate the n-th optical code signal; however, as will be described later on with reference to

25   Embodiment 2-8 of the second mode of working of the present invention, it is also possible to use chip light sources each of which corresponds to one chip forming the encoding code, for example, outputs an optical signal of a single

optical frequency. In this instance, those of the chip light sources corresponding to the chips "1" forming the encoded code Cn(f) output optical signals but those chip light sources corresponding to the chips "0" do not output optical signals; that is, the chip light sources responds to the encoding

5    code Cn(f) to provide the optical signals for the mark but not to provide the optical signals for the space.

[0063] The encoded code in Embodiment 1-3 has such characteristics as described below. When two arbitrary encoding codes are selected from among different encoding codes of the same code length FCL, they satisfy at

10    least one of the following conditions:

Number of chip positions in chip strings of the first and second encoding codes where their corresponding chips simultaneously go to "1s" is equal to the numbers of chip positions where the first encoding code goes to a "1" and the second encoding code goes to a "-1"; or

15    Number of chip positions where the first and second encoding codes simultaneously go to "-1s" is equal to the numbers of chip positions where the first encoding code goes to a "-1" and the second encoding code goes to a "1"; and they also satisfy the following condition:

Numbers of chips "1" and chips "-1" in a continuous string of chips of

20    the afore-mentioned code length FCL arbitrarily extracted from the concatenated code of a continuous repetition of the encoding codes are equal to each other irrespective of any particular strings of chips; and they also satisfy at least one of the following conditions:

Number of chip positions where first and second continuous strings of

25    chips of the code length FCL, arbitrarily extracted from different concatenated codes of continuous repetitions of two different encoding codes, simultaneously go to "1s" and the chip positions where first chip string goes

to a "1" and the second ship string goes to a "-1" are equal to each other; or

Number of chip positions where the first and second chip strings simultaneously go to "-1s" and the number of chip positions where the first chip string goes to a "-1" and the second chip string goes to a "1" are equal to

5    each other.    And the chips forming the encoding code are sequentially assigned consecutive optical frequencies corresponding to the chip strings.

[0064] The source optical frequency width FSR is a natural-number multiple of the code length FCL of each encoding code Cn(f), and the optical frequency region 31 for encoding by each encoder $11_n$ the optical frequency

10    region 32 for decoding by each decoder $12_n$ are both within the optical frequency range from Fst to Fla, where Fla − Fst > FSR.    And it is evident that Cn(f) = Cn(f + FCL) holds in FSR in the range from Fla to Fst and that Eq. (13) holds between the code Cn(f) and its complementary code (1 - Cn(f)) as follows:

15    $$\int Cn(f) \cdot Cn(f)df > \int Cn(f) \cdot (1 - Cn(f))df \qquad (14)$$

where $\int df$ represents a definite integral with respect to f in an arbitrary interval FSR in the optical frequency range from Fst to Fla.

[0065] It is also clear that Cn(f) bears the relationship of the following equation (15) to the encoding code Cm(f).

20    $$\int Cn(f) \cdot Cm(f)df = \int Cn(f) \cdot (1 - Cm(f))df \qquad (15)$$

In Embodiment 1-2, as is evident from Eq. (7), it is possible to use, for each Cn(f), r' (typically, r' = 2) encoded codes with a = n.

[Second Mode of Working] (Optical Phase·Amplitude Modulation)

The second mode of working of the present invention is intended as a

25    solution to the problems of the prior art through phase modulation and phase or amplitude modulation of a carrier on the optical frequency axis.

[Embodiment 2-1]

Fig. 30 illustrates an optical communications system according to Embodiment 2-1 of the second mode of working of the invention. In an optical transmitter 100 a transmission signal from an input terminal 101, usually a binary data sequence signal, is converted by a signal-phase

5    converter 110 into a phase shift (phase shift value) sequence or modulation phase sequence (hereinafter referred to also as a modulation unit sequence), where the value of phase shift corresponding to every V pieces of data (where V is an integer equal to or greater than 1) is less than one period. An optical signal from a light source 120 is fed to a phase modulation part 130, wherein

10    the phase of a pseudo-carrier on the optical frequency (wavelength) axis starting at a predetermined optical frequency (wavelength) as a reference is shifted to each phase amount from the signal-phase converter 110. The pseudo-carrier will sometimes be referred to simply as a carrier.

[0066] The term "pseudo-carrier" corresponds to the term "optical frequency

15    characteristic (function)," "encoded code or decoded code," or "optical filtering frequency characteristic (function)" in other modes of working." Since in the second mode of working of the invention the pseudo-carrier on the optical frequency axis is subjected to a modulation similar to QPSK or QAM modulation for the carrier on the time axis used in radio

20    communications, the term "pseudo-carrier" will be used primarily in the interests of better understanding of the invention.

For example, as shown in Fig. 31, the data sequence is divided into data sets each consisting of V = 2 pieces of data, and the data sets are each assigned a different phase shift amount, that is, a phase amount shifted from a

25    reference phase 0 (which will hereinafter refer to the phase shift amount). For example, data sets (0, 0), (0, 1), (1, 0) and (1, 1) are converted to phase amounts $0$, $\pi/2$, $\pi$, $3\pi/2$, respectively, which are less than one period.

[0067] Assume that an optical frequency difference from the reference optical frequency fs is a phase f, 400 GHz is one period $\Lambda$, and an optical signal that is coded by a function which is obtained, by adding 1 to and dividing by 2, a trigonometric function that means the optical intensity of each optical

5  frequency signal, is the pseudo-carrier.   When the phase f is 0, $\pi/2$, $\pi$, and $3\pi/2$, the optical frequency characteristics become as shown in Figs. 31(a) to 31(d), respectively; that is, for each $\pi/2$ shift of the phase f, the optical frequency shifts by 100 GHz.   In Figs. 31(a) to 31(d) the leftmost diagrams each show the pseudo-carrier in terms of vector on a complex plane, the

10  second from the left the instantaneous phase-intensity characteristic of the pseudo-carrier and the leftmost its optical intensity-frequency characteristic.
[0068] Letting an n-multiple of the period $\Lambda$ of the pseudo-carrier be represented by FSR, that is, FSR = $n\Lambda$ (where n = 1, 2, ...), the light source 120 outputs an optical signal of at least the optical frequency width FSR.

15  The output optical signal from the phase modulation part 130 is ((1 + cos($2\pi fn$/FSR + $\Theta$)))/2 whose phase shift amount is any one of $\Theta$ = 0, $\pi/2$, $\pi$ and $3\pi/2$.

In an optical receiver 200 the received light is split by a splitter 210 for input to four filters 221, 222, 223 and 224 corresponding to the phase shift

20  amounts 0, $\pi/2$, $\pi$ and $3\pi/2$, respectively, the intensity of light transmitted through the filters 221, ..., 224 is detected by detectors 231, ..., 234.   The outputs from the detectors 231, 233 and the outputs from the detectors 232, 234 having detected output light intensities of the filters corresponding to the phase shift amounts displaced one-half period apart, respectively, are

25  subtracted from each other by comparators 241 and 242, respectively.   The outputs from the comparators 241 and 242 are converted by a code-signal converter 250 to a data set corresponding to the phase shift amount of the

pseudo-carrier, which is output as a decoded data sequence.

[0069] Figs. 32-1 to 32-4 show examples of: the wavelength characteristic of the light source 120 and the intensity-time characteristic of the light source in the case of using a pulse light source; the optical output from the modulation

5      part 130 corresponding to each shift amount $\Theta$ (the optical output from the optical transmitter 100); the filtering characteristic of each filter of the receiver 200; the transmission-intensity characteristic of each filter for each phase shift amount; and temporal variations of the detected intensity of each detector.    The leftmost column of each diagram shows the output light from

10     the light source 120; it is assumed, in this case, that the optical frequency width of the output light is 400 GHz and that the output optical intensity is flat over its entire wavelength range.    The columns second from the left in Figs. 32-1 to 32-4 show optical frequency characteristics of the output light from the phase modulation part 130 corresponding to the phase shift amounts

15     0, $\pi/2$, $\pi$ and $3\pi/2$, respectively.    The columns third from the left show filtering characteristics of the filters 221, 223, 222 and 224 of the optical receiver, respectively.    The columns fourth from the left in Figs. 32-1 to 32-4 show frequency characteristics of transmitted light through the filters 221, 223, 222 and 224 in the cases where they receive the optical outputs from the

20     modulator depicted in Figs. 32-1 to 32-4, respectively.    The rightmost columns in Figs. 32-1 to 32-4 show temporal variations of the intensity detected by the detectors 231, ..., 234, respectively.    As shown in Figs. 32-1 to 32-4, letting the power of the source output light be represented by 1, the detected intensity of the output from the filter, which has a filtering

25     characteristic identical with the optical frequency characteristic of the modulator output light corresponding to the amount of phase shift from the reference in the modulation part 130, is 0.375 (first row in Fig. 32-1 and

second row in Fig. 32-2), and the detected intensity of the output from the filter whose filtering characteristic is displaced π apart from the filtering characteristic of the above-mentioned filter is 0.125 (third row in Fig. 32-1 and fourth row in Fig. 32-4), and the output from the comparator that

5  compares the detected intensities is 0.25.   On the other hand, the detected intensities of the outputs from the filters, whose filtering characteristics are displaced π/2 and 2π/3 apart from the frequency characteristic of the modulator output light corresponding to the phase shift amount relative to the reference in the modulation part 130, are 0.25 (second and fourth rows in Fig.

10  32-1 and third and first rows in Fig. 32-2); consequently, the comparator which compares the intensity-detected outputs provides an output 0.

[0070] A description will be given below of the output intensity of the comparator in the case of comparing intensities of optical pulses of the transmitted light through the filters, not in the case where the detectors detect

15  transmitted light intensities for each optical frequency component and the comparators compare the detected intensities.

The output light from the phase modulation part 130 is given by the following equation.

$$(1/2\pi) \int ((1 + \cos(2\pi f/\text{FSR} + \Theta))/2)df \qquad (16)$$

20  where f represents an optical frequency difference from a reference optical frequency, and n = 1.

(1) In the case of the comparator output corresponding to the filters which have a filtering characteristic identical with the optical frequency characteristic of the phase modulator output light corresponding to the phase

25  shift amount of the input to the phase modulation part 130:

$$(1/2\pi) \int ((1 + \cos(2\pi f/\text{FSR} + \Theta))/2) ((1 + \cos(2\pi f/\text{FSR} + \Theta))/2)df$$
$$- (1/2\pi) \int ((1 + \cos(2\pi f/\text{FSR} + \Theta))/2) ((1 + \cos(2\pi f/\text{FSR} + \Theta + \pi))/2)df$$

$$= (1/8\pi) \int (1 + \cos 2(2\pi f/FSR + \Theta) + 2 \cos(2\pi f/FSR + \Theta))df = 0.25$$

$$(17)$$

The first and second terms on the left side correspond, for example, to the output from the detector 231 and the output from the detector 233, respectively.

(2) In the case of the comparator output corresponding to the filters which have a filtering characteristic phase $\pi/2$ apart from the optical frequency characteristic of the phase modulator output light corresponding to the phase shift amount of the input to the phase modulation part 130:

$$(1/2\pi) \int ((1 + \cos(2\pi f/FSR + \Theta))/2)((1 + \cos(2\pi f/FSR + \Theta + \pi/2))/2)df$$

$$(18)$$

$$- (1/2\pi) \int ((1 + \cos(2\pi f/FSR + \Theta))/2)((1 + \cos(2\pi f/FSR + \Theta - \pi/2))/2)df$$

$$= (1/8\pi) \int (- 2 \sin(2\pi f/FSR + \Theta) + \sin 2(2\pi f/FSR + \Theta))df = 0$$

$$(19)$$

In this embodiment the number M of the phase shift amounts (phase shift values) possible for the pseudo-carrier is an even number 4, and since these phase shift amounts (phase shift values) are sequentially displaced $\pi/2$ apart, the receiving side uses filters of the same number as M, but in the case where the phase shift amounts (values) that the pseudo-carrier is allowed to take are not displaced $\pi$ apart, the receiving side uses filters of the same characteristics as those of the output light of the phase shift amounts (values) that the pseudo-carrier is allowed to take and filters of characteristics phased the half period ($\pi$) apart from the output light of the phase shift amounts (values) that the pseudo-carrier is allowed to take. Accordingly, the optical receiver 200 requires 2M filters and comparators of the same number as M. In this instance, the value M is arbitrary, but the phase shift amounts (phase shift values) of the carrier by the phase modulation part 130 needs to be phase

shift amounts (phase shift values) which differ in the remainder $\Delta$ of the trigonometric function over one period for each of them.

[0071] This embodiment has been described on the assumption that the optical frequency characteristic of the output light from the light source 120 is flat, but when it is not flat, for example, Gaussian, the transmitting-side phase modulation part or the receiving-side filters, comparators or detectors need only to assign weights to their outputs so as to level off intensity at each optical frequency.

While in this embodiment the invention has been described above as using a combination of the single optical transmitter 100 and the optical receiver 200, the invention is applicable as well to the case where other optical transmitter and optical receiver share the same optical transmission line 300, in which case the following settings are made.

[0072] 1) Where the reference optical frequency fs in the optical transmitter is displaced FSR or more: FSR and the phase shift amounts (phase shift values) are both arbitrary.

2) Where the reference optical frequency fs in the optical transmitter is displaced less than FSR: The optical frequency of the light source 120 that is used in the same FSR is the same, and the filters ought to continuously filter not only the optical frequency of the optical transmitter own FSR but also the optical frequencies used by the other optical transmitters which share the same optical transmission line. The value, FSR/n, of the carrier period is different for each optical transmitter. When the period FSR/n is common to all the optical transmitters, letting the number of phase shift amounts (shift values) for modulation by the phase modulation part 130 be represented by M inclusive of the 0-phase, the value of addition of FSR/n/M to the reference optical frequency fs ought to be unique to every optical transmitter.

However, when different sets of optical transmitters and receivers use the same value n, only those optical frequency signals displaced a quarter period apart are orthogonal to each other, and consequently, M is 4, whereas those optical frequency signals displaced a half period apart are used by the optical

5    transmitter and receiver of the same set.

[0073] In the case of 1), when the reference optical frequencies fs for use in multiple optical transmitters are displaced FSR or more apart, different optical frequencies are used, so no interference occurs between carriers, irrespective of the pseudo-carrier.

10    In the case of 2), when the multiple optical transmitters use the same reference optical frequency fs, they use the same optical frequency. However, since the frequency of the pseudo-carrier used by each optical transmitter is a natural-number fraction of FSR, the integration value of their scalar product over an interval FSR is zero and they are orthogonal to each

15    other, incurring no interference between the carriers.

When the multiple optical transmitters use different reference optical frequencies fs displaced less than FSR apart, since the functions of the carriers are periodic functions within FSR, use is made of filters which modulate optical frequencies outside FSR with the same function as that for

20    the pseudo-carrier, and if the optical frequencies of light sources are substantially equal, the integration value of their scalar product is zero and they are orthogonal to each other, incurring no interference between the carriers.

[0074] The phase modulation part 130 for use in this embodiment comprises,

25    as shown in Fig. 30, a filter 131 and a modulator 132 for changing its filtering characteristic.

Fig. 33 illustrates an example of the configuration of the filter 131.

A Mach-Zehnder interferometer is used which divides the input light by a coupler 131a into two optical signals for input to two optical paths 131b and 131c having a predetermined path length difference and combines the optical signals again by a coupler 131d, and the modulator 132 is one that is inserted

5    in the one optical path 131b of the Mach-Zehnder interferometer to change the path length difference between the two optical paths.    The optical signals having passed through the optical paths 131b and 131c interfere with each other in the coupler 131d, which outputs components spaced apart the optical frequency corresponding to the path difference.    The optical frequency

10   characteristic of the output light is periodic; therefore, assuming that the frequency difference between the optical outputs is 100 GHz, for instance, there will be obtained the filtering characteristic shown in the rightmost column of Fig. 31(a).    With the use of the filter 131 which periodically filters optical frequencies like Mach-Zehnder interferometer, it is possible to

15   eliminate interference even if multiple optical transmitters use different reference optical frequencies fs displaced each other less than FSR apart.
[0075] To change the path length, the optical paths are integrated on a planar lightwave circuit substrate as shown in Fig. 9, and a phase shift amount signal from the signal-phase converter 110 is applied to the electrode 49 to change

20   the delay amount of the optical path associated with the electrode.    In this instance, the filter 131 and the modulator 132 are not series-connected but instead they are integrally formed with each other.    That is, the modulator 132 is incorporated into the filter 131.

The signal-phase converter 110 in the optical transmitter 100 is

25   configured, for example, as shown in Fig. 30, in which the data sequence from the input terminal 101 is converted by a serial-parallel converter 110a to two sequences, the two pieces of data of the two data sequences from the

serial-parallel converter 110a are converted by a D/A converter 110b to digital values 0, 1, 2 and 3 corresponding to combinations of the input data (0, 0), (0, 1), (1, 0) and (1, 1), respectively, and voltages corresponding to these values are applied to the electrode 49 in Fig. 9.   In accordance with the applied

5    voltage values the phase of the pseudo-carrier of the output light from the phase modulation part 130 varies as shown in Figs. 31(a) to 31(d).

[0076] The filter 131 in the optical transmitter 100 filters light from the light source 120 at least over the optical frequency width FSR, and the filtering characteristic, that is, the transmittance (optical intensity)-optical frequency

10   characteristic is such that when the optical frequency difference from the reference optical frequency fs is used as phase, the transmittance (optical intensity) in each phase conforms to a function obtained, by adding 1 to and dividing by 2, a trigonometric function indicating the period obtained by dividing FSR by a natural number n.

15         A code signal converter 250 in the optical receiver 200 is configured, for example, as depicted in Fig. 1, in which outputs 0 or 1 from the comparators 241 and 242 are input in parallel to a parallel-serial converter 251, from which they are output as a single sequence of data signals to an output terminal 201.   Thus, the transmission signal input to the input

20   terminal 101 of the optical transmitter 100 is regenerated and output to the output terminal 201.

[0077] As described above, according to Embodiment 2-1, in order to emulate positive- or negative-polarized uncorrelated carriers by non-polarized intensity modulation which is a part of a repetition of a desired frequency

25   period on the optical frequency axis, use is made of broadband light of an optical frequency width which is a natural-number of multiple of the pseudo-carrier period and a differential detection is conducted on the

receiving side to inhibit the input thereto of pseudo-carriers other than those to be received; thus, even if light of the same optical frequency is used, the correlation between pseudo-carriers is eliminated which is attributable to trigonometric functions that are not orthogonal to each other in a finite optical

5    frequency width, the uncorrelated pseudo-carriers are emulated, and the emulated pseudo-carriers are phase-modulated--this permits implementation of MPSK with control accuracy lower than that on the order of the wavelength of light.    It will be described later on that the second mode of working of the invention is basically common in technical idea to the first

10   mode of working.

[Embodiment 2-2]

    In Embodiment 2-1, the modulator 132 of the phase modulation part 130 controls the phase of the pseudo-carrier of light filtered or to be filtered by the filter 131.    According to Embodiment 2-2, for example, as shown in

15   Fig. 34, the phase modulator is provided with a plurality of filters 133a, 133b, 133c and 133d each of which filters the optical frequency corresponding to the phase shift amount (value) that is the amount of modulation, and the light from the light source 120 is input via a splitter 134 to the filters 133a to 133d. The optical outputs from the filters 133a to 133d are selected and output by

20   the modulator 132 in accordance with the modulation phase amount (value). For example, the filters 133a to 133d have the filtering characteristics that the carrier phases are $0$, $\pi/2$, $\pi$, and $3\pi/2$ as shown in Figs. 31(a) to 31(d), respectively, and the optical outputs from the filters 133a to 133d are input to optical switches 135a to 135d which form the modulator 132.    In the

25   signal-phase converter 110, the two pieces of data output from the serial-parallel converter 110a are decoded by a decoder 110c, which provides outputs at its output terminals 111a, 111b, 111c and 111d corresponding to the

data sets (0, 0), (0, 1), (1, 0) and (1, 1), respectively, and by the output at each of the output terminals 111a to 111d the corresponding one of the switches 135a to 135d is turned ON. The optical outputs from the switches 135a to 135d are provided via a combiner 136 to the transmission line 300.

5    [0078] As indicated by the broken line in Fig. 34, the switches 135a to 135d of the modulator 132 may be disposed between the splitter 134 and the filters 133a to 133d to combine the transmitted outputs from the filters 133a to 133d by the combiner 136. Both the splitting stage and the combining stage may be incorporated into the modulator 132 which inputs the light from the light

10   source only to a selected one of the filters and transmits the light from the selected filter.

Unlike Embodiment 2-1, Embodiment 2-2 eliminates the need for selecting the material which allows switching of the optical path length difference in a time to modulate. Incidentally, the optical receiver 200 may

15   be one that is shown in Fig. 30. While in the above this embodiment has been described in connection with the case where the number M of phase shift amounts (values) possible for the pseudo-carrier is 4, the number M may be arbitrary.

[Embodiment 2-3]

20   In Embodiment 2-3 a set of two pseudo-carriers displaced $\pi$ apart in phase and a different set of pseudo-carriers displaced $\pi/2$ apart in phase are made to correspond to two sets of data of the transmission signal. Fig. 35(a) shows an example of the optical transmitter according to Embodiment 2-3. The conditions for the light source 120 and the filters are the same as those in

25   Embodiments 2-1 and 2-2. The filtering characteristics of two filters of each set are displaced $\pi$ apart in phase, that is, their transmitted optical frequencies are displaced FSR/2/n apart. Letting the pseudo-carrier for use in this

embodiment be identified as an i-th carrier and setting $2\pi f = \Theta$, characteristic functions of the respective sets are Ci $(\Theta)$ or Ci$(\Theta + \pi)$ and Ci$(\Theta + \pi/2)$ or Ci$(\Theta + 3\pi/2)$, and assuming that $\int d\Theta$ is a definite integral over the interval FSR, the following equations hold.

5  [0079]  $\int$Ci$(\Theta)$(Ci $(\Theta + \pi/2)$ – Ci'$(\Theta + \pi/2)$)d$\Theta$ = $\int$Ci$(\Theta)$(Ci $(\Theta + 3\pi/2)$

$$– Ci'(\Theta + \pi/2))d\Theta = 0 \qquad\qquad (20)$$

$$\int Ci(\Theta)(Ci (\Theta) – Ci(\Theta))d\Theta = \int Ci(\Theta + \pi)(Ci (\Theta + \pi) – Ci'(\Theta + \pi))d\Theta$$

$$(21)$$

Fig. 36(a) shows QPSK signal points (coordinate points) on a complex

10  coordinates, and Fig. 36(b) shows, by way of example, signal data sets, coordinate points and sets of select filtering phases in the case of emulating QPSK.   In this instance, the number of sets M/2 = 2, the phase shifts of the one data set are 0 and $\pi$, and the phase shifts of the other data set are $\pi$2 and $3\pi/2$, and their coordinate points are shown on a unit circle in Fig. 36(a).   0

15  and $\pi$ in the data set of phase shifts 0 and $\pi$ correspond to 1 and -1 on the x-axis, respectively, whereas $\pi/2$ and $3\pi/2$ in the data set of phase shifts $\pi/2$ and $3\pi/2$ correspond to 1 and -1 on the y-axis, respectively.   The coordinate points are indicated in the parentheses with the x-axis values at the left-hand side and the y-axis values at the right-hand side.

20  [0080] The phase modulation part 130 outputs light of the pseudo-carrier of the 0-phase shift or $\pi$-phase shift corresponding to one bit of the two-bit data set, in the example of Fig. 36(b), the high-order bit (data) a 0 or 1 and outputs light of the pseudo-carrier of the $\pi/2$-phase shift or $3\pi/2$-phase shift corresponding to the low-order bit (data) a 0 or 1.   That is, it can be said that

25  the output from the phase modulation part is an optical code signal indicating the combination codes of the two pieces of data in the data sequence for each modulation unit of the pseudo-carrier light output from the phase modulation

part.

In the example of Fig. 35(a), as is the case with Fig. 34, filters 133a to 133d are provided each corresponding to one of the pseudo-carriers; the 0-phase filter 133a and the $\pi$-phase filter 133c are combined, and the

5    $\pi/2$-phase filter 133b and the $3\pi/2$-phase filter 133d are combined. Switches are provided as modulators 132a and 132b, and the switch as the modulator 132a is controlled by the high-order bit of the serial-parallel converter 110a of the signal-phase converter 110; the switch as the modulator 132a is connected to the 0-phase filter 133a or $\pi$-phase filter 133c, depending on whether the

10    high-order bit (data) is a "0" or "1." The switch as the modulator 132b is controlled by the low-order bit (data) of the serial-parallel converter 110a in such a manner that the switch is connected to the $\pi/2$-phase filter 133b or $3\pi/2$-phase filter 133d, depending on whether the low-order bit is a "0" or "1." The transmitted light through the filters selectively switched by the switches

15    as the modulators 132a and 132b is output via the combiner 136 to the optical transmission line 300.

[0081] That is, the input data sequence from the terminal 101 is applied to the serial-parallel conversion part (hereinafter referred to as a sequence converting part) 110a, wherein it is sequentially separated into first data

20    sequence (a low-order bit sequence) and a second data sequence (a high-order bit sequence); a modulation part 132b and a modulation part 132a are controlled according to values of respective pieces of data of the first and second separate data sequences to outputs optical code signals of pseudo-carriers (optical intensity-frequency characteristics) corresponding to

25    the data values, respectively, and these optical code signals are combined into an output optical code signal.

The modulators 132a and 132b may be adapted to select the filter to

which light is input. For example, as shown in Fig. 35(b), the light emitted from the light source 120 is split by a splitter 134 into two, the one splitter of which is selectively fed into the 0-phase filter 133a or π-phase filter 133c via a switch serving as a modulator 132a, and the other of which is selectively fed into to the π/2-phase modulator 132b or 3π/2-phase modulator 132d via a switch serving as a modulator 132b, and the optical outputs from the filters 133a to 133d are provided via the combiner 136 to the optical transmission line 300. On both of the input and output sides of the filters 133a to 133c modulators may be disposed as switches, permitting the passage of light from the light source through only a selected one of the modulators.

[0082] The optical receiver corresponding to this embodiment may be of the same configuration as shown in Fig. 30. In such an instance, however, since the comparators 241 and 242 output +1s or −1s, converting parts 241a and 242a are used in the optical transmitter 200, as indicated by the broken lines in Fig. 30, to convert −1s to 0s, which are provided to the code converter 250. It will be easily be understood that the code converter 250 thus provides the same signal sequence as the input transmission signal sequence to the optical transmitter 100.

In this way, QPSK can be implemented with a lower degree of control accuracy on the order of optical wavelength.

[Embodiment 2-4]

Embodiment 2-4 emulates 16-QAM by use of pseudo-carriers. In this embodiment, two sets of pseudo-carriers, each consisting of two pseudo-carriers displaced half a period (π) apart in phase, are used to emulate light from the light source according to 16 kinds of data sets in this example, the pseudo-carriers of the one and the other set are phased a quarter period (π/2) apart and orthogonal to each other, and optical signals with these four

pseudo-carriers of light intensities (amplitudes) having either one of two values are combined and transmitted.

[0083] Figs. 37-1 and 37-2 illustrate examples of embodiment 2-4. The optical transmitter 100 shown in Fig. 37-1 uses four filters 133a to 133d for

5    generating 0-, $\pi/2$-, $\pi$- and $3\pi/2$-phase pseudo-carriers. The conditions for the light source 120 and the filters 133a to 133d are the same as in the case of Embodiment 2-3.

Fig. 38(a) shows signal points (coordinate points) and data sets on the coordinates (the x-axis representing the real part and the y-axis the imaginary

10    part) in th case of 16QAM, and Fig. 38(b) shows the relationships of phase shifts and light intensities (amplitudes) of the pseudo-carriers to the respective data sets. For example, in the case where the data set is (0000), light of a pseudo-carrier of 0-phase shift and optical intensity 3 and light of $\pi/2$-phase shift and intensity 3 are output to the transmission line 300, and in the case of

15    the data set (0101), light of a pseudo-carrier of 0-phase shift and optical intensity 3 and light of $3\pi/2$-phase shift and intensity 1 are output to the transmission line 300. The transmission signal sequence from the terminal 101 is converted every four data sets by a signal-to-phase and amplitude converter 140 to the phase and amplitude information indicating the phase

20    shift and the amplitude in Fig. 38(b), and the light from the light source 120 is modulated by a phase and amplitude modulating part 150 to two optical signals of the pseudo-carrier phases and intensities corresponding to the above-mentioned phase and amplitude information, which optical signals are output to the optical transmission line 300.

25    [0084] In the signal-to-phase and amplitude converter 140, the input transmission signal sequence is divided, for example, by a serial-parallel converter 110c, into four signal sequences. The phase-amplitude modulating

part 150 is, in this embodiment, formed by filters 133a, 133b, 133c and 133d for the pseudo-carriers of phase shifts 0, $\pi/2$, $\pi$, $3\pi/2$, respectively, two modulators 151, 152, and a combiner 136. Upon each output of a 4-bit (data) set consisting of four bits (data) extracted one by one from the four

5    signal sequences output from the serial-parallel converter 110b, the switch 151a in the modulator 151 is controlled by the high-order (leftmost in Fig. 38(b)) data of the 4-data set; the switch 151a is connected to the 0-phase filter 133a or $\pi$-phase filter 133c, depending on whether the data is 0 or 1; and the output light from the switch 151a is provided to the combiner 136 via an

10    amplitude changing part 151b wherein the intensity of the output light is controlled by the third high-order data of the data set to go to a 3 or 1, depending on whether the data is a 0 or 1. In the modulator 152 the switch 152a is connected to the $\pi/2$-phase filter 133b or $3\pi/2$-phase filter 133d, depending on whether the second high-order data of the 4-data set is a 0 or 1,

15    and the output light from the switch 152a is provided to the combiner 136 via an amplitude changing part 152b wherein the intensity of the output light is controlled by the low-order data of the 4-bit data set to go to a 3 or 1, depending on whether the data is a 0 or 3.

[0085] That is, the input data sequence from the terminal 101 is sequentially

20    separated by the serial-parallel converting part (hereinafter referred to as a sequence converting part) 110c into first to fourth separate data sequences: the phase modulation part 152a is controlled according to the value of each piece of data of the third separate data sequence, the phase modulation part 151a is controlled according to the value of each piece of data of the fourth separate

25    data sequence, the amplitude changing part 152b is controlled according to the value of each piece of data of the first separate data sequence, and the amplitude changing part 151b is controlled according to the value of each

piece of data of the second separate data sequence.

The modulators 151 and 152 may also be inserted between the light source 120 and the filters 133a to 133d as depicted in Fig. 39. In this instance, the light from the light source 120 is split by the splitter 134 into two,

5   one of which is input first to the modulator 151, wherein its intensity is controlled by the amplitude changing part 151b to go to a 3 or 1 according to the third high-order data, and the thus intensity-controlled light is output via the switch 151a to the 0-phase filter 133a or $\pi$-phase filter 133b according to the highest-order data. The other split light from the splitter 134 is input

10   first to the modulator 152, wherein its intensity is controlled by the amplitude changing part 152b to go to a 3 or 1 according to the lowest-order data, and the thus intensity-controlled light is output via the switch 152a to $\pi/2$-phase filter 133b or $3\pi/2$-phase filter according to the second high-order data.

[0086] It is also possible to intensity-control the optical inputs to the two sets

15   of filters by the amplitude changing parts 151b and 152b according to the third high-order data and the lowest-order data, respectively, and select the filters of the two sets of filters by the switches 151a and 152a according to the highest-order data and the second high-order data, respectively. Alternatively, it is possible to input the light from the light source to either

20   one of the two filters of each set and intensity-control the optical outputs from the filters of the two sets by the amplitude changing parts 151b and 152b, respectively.

The optical receiver 200 uses, as shown in Fig. 37-2, the same filters 221-224, detectors 231 to 234 and comparators 241, 242 as those shown in

25   Fig. 30, but uses, as a substitute for the code signal converter 250, a code signal converter (data generating means) 260 of the type that converts the outputs from the comparators 241 and 242 to a set of four pieces of data

corresponding to two levels (intensities) including polarities (positive and negative), that is, four levels, and outputs these data in serial form. In other words, the comparators 241 and 242 each outputs any one of 3, 1, −1 and −3 shown in Fig. 38(b); and a data set shown in Fig. 38(b) is provided

5  corresponding to such a combination of the outputs.

[0087] In such a code signal converter 260, for instance, as depicted in the optical transmitter of Fig. 37-2, the outputs from the comparators 241 and 242 are converted by A/D converters 262 and 262 to 3-bit digital values each containing a sign (code); these 3-bit (a total of 6 bits) digital values are used

10  as addresses to read a conversion memory 265 to obtain therefrom a data set of such four corresponding bits as depicted in Fig. 38(b), and the output data set is converted by a parallel-serial converter (data generating means) 266 to serial data, which is provided to an output terminal 201. Incidentally, let it be assumed that the relationships between the addresses thereto and the data

15  to be read out thereof are prestored in the conversion memory 265 in such a manner as to obtain the relationships between the comparator outputs and the data sets shown in Fig. 38(b).

[0088] As described above, according to Embodiment 2-4, as is the case with Embodiment 2-1, in order to emulate positive- or negative-polarized

20  uncorrelated carriers by non-polarized intensity modulation which is a part of a repetition of a desired frequency period on the optical frequency axis, use is made of broadband light of an optical frequency width which is a natural-number multiple of the pseudo-carrier period and a differential detection is conducted on the receiving side to inhibit the input thereto of

25  pseudo-carriers other than those to be received; thus, even if light of the same optical frequency is used, the correlation between pseudo-carriers is eliminated which is attributable to trigonometric functions that are not

orthogonal to each other in a finite optical frequency width, the uncorrelated pseudo-carriers are emulated, then the simulated pseudo-carriers are phase-modulated, then multiple pseudo-carriers which are orthogonal to each other are intensity-modulated with the half period and transmitted at the same time--this permits implementation of QAM with control accuracy lower than that on the order of the wavelength of light.

[Embodiment 2-5]

While the above-described embodiment uses the pseudo-carriers that vary in an analog fashion on the optical frequency axis, but Embodiment 2-5 uses pseudo-carriers that are turned on and off in a digital fashion on the optical frequency axis. The optical transmitter 100 includes, as shown in Fig. 40, the signal phase-amplitude converter 110 and the phase modulation part 160 made up of the filter 137 which divides the light from the light source 120 into multiple chips on the optical frequency (wavelength) axis and selectively transmits them, and the modulator 132.

[0089] Let FSR represent the optical frequency width of the light from the light source 120.

The filter 137 receives the light from the light source 120, filters the light from the light source 120 which has the optical frequency width FSR, then divides on the optical frequency axis the light of the frequency width FSR from the light source into L (a multiple of 4) chips, and selectively transmits them. The selection of chips that are allowed to pass through the filter is mapped into phase values as described below. Now, let the divider of L/4 be represented by S. Fig. 41 shows examples of filtering characteristics.

0-phase filter 137a: Filter by repeatedly turning ON (pass) consecutive 2S chips and OFF (interrupt) the next 2S chips until L is reached.

[0090] $\pi/2$-phase filter 137b: Filter by repeatedly turning OFF (interrupt) consecutive S chips, then ON (pass) the next 2S chips, and OFF (interrupt) the next S chip until L is reached.

$\pi$-phase filter 137c: Filter by repeatedly turning OFF (interrupt) consecutive 2S chips and ON (pass) the next 2S chips until L is reached.

$3\pi/2$-phase filter 137d: Filter by repeatedly turning ON (pass) consecutive 2S chips, then OFF (interrupt) the next 2S chips, and OFF (interrupt) the next S chip until L is reached.

[0091] In Fig. 41 there are shown filtering frequency characteristics of the filers 137a, 137b, 137c and 137d, for example, in the case where L = 4 and S = 1. In Figs. 41(a), 41(b), 41(c) and 41(d) where FSR/n corresponding to 4S chips is one period on the optical frequency axis and one-half the period corresponds to 2S chip, i.e., one period is 2 $\pi$, there are shown filtering characteristics of the filters 137a, 137b, 137c and 137d which permits the passage therethrough of light of 2S chips of $\pi$-width shifted to 0-, $\pi/2$-, $\pi$- and $3\pi/2$-phase positions, respectively. Accordingly, the light having passed through these filters 137a, 137b, 137c and 137d becomes such that a pseudo-carrier of the period FSR/n on the optical frequency (wavelength) axis, which is a rectangular pattern of the $\pi$-width, that is, of a 50% duty ratio, is phase-modulated to 0, $\pi/2$, $\pi$ and $3\pi/2$, respectively.

[0092] Embodiment 2-5 enables implementation of the QPSK modulation by associating two pseudo-carriers of such phases and two data sets. In Embodiment 2-5, since the filters 137a, ..., 137d are associated with 0, ..., $3\pi/2$, respectively, the two pieces of data from the signal-to-phase converter 110 are used, as is the case with the optical transmitter of Fig. 35(a), to control the modulators 132a and 132b to select the output light from the 0-phase filter 127a or the output light from the $\pi$-phase filter 137c and the

output light from the $\pi/2$-phase filter 137b or the output light from the 3$\pi/2$-phase filter 137d, and the optical outputs thus selected are output via the combiner 136 to the optical transmission line 300.

[0093] As depicted in Fig. 35(b), the modulators 132a and 132b may be

5    connected to the input sides of the filters 137a to 137d. Also, modulators may be connected to input and output sides of the filters 137a to 137d.

The optical receiver 200 in Embodiment 2-5 is identical in construction with the optical receiver shown in Fig. 30 except that 0-, $\pi/2$-, $\pi$- and 3$\pi/2$-phase filters 225, 226, 227 and 228 of the same filtering

10   characteristics as those of the filters 137a to 137d, respectively, are used in place of the filters 221 to 224 in the optical receiver 200 depicted in Fig. 30. Accordingly, the parts corresponding to those in Fig. 30 are identified by the same reference numerals and the filters are denoted by parenthesized reference numerals in Fig. 37-1.

15   [0094] Figs. 42-1 to 42-2 show examples of the optical frequency characteristic of the light source 120 and the optical intensity-time characteristic of a pulse light source used as the light source, modulation part outputs (transmitter outputs) corresponding to respective phases, filtering characteristics of respective filters in the receiver, light having passed through

20   the filters of the receiver for transmitted outputs in respective pseudo-carrier phases; and temporal changes of the intensity detected by the respective detectors in Embodiment 2-5. In each figure, the leftmost column shows the optical source output. The source output is shown in terms of an optical frequency difference from the reference optical frequency fs, with the optical

25   frequency width of the light source 120 assumed as 400 GHz and the intensity of the source output assumed as being flat over the entire optical frequency range. In Figs. 42-1 to 42-4 the columns second from the left-hand side

show modulation part outputs corresponding to the phase shifts 0, $\pi/2$, $\pi$, $3\pi/2$, respectively. In the columns third from the left-hand side, the filtering characteristics (functions) of the filters 225 to 228 in the optical receiver 200 are shown in first to fourth rows of the columns, respectively. In each of

5     Figs. 42-1 to 42-4 the column fourth from the left-hand side shows in its first to fourth rows the optical frequency characteristics of light passing through the filters 225 to 228 in the case where the modulation part outputs shown there are input to the filters, respectively. The rightmost columns show in their first to fourth rows temporal changes of the intensities to be detected by

10     the detectors 231 to 234, respectively.

[0095] As shown in Figs. 42-1 to 42-4, assuming that the power at the detector at the time of all the chips passing through the filters is 1, the detected intensity corresponding to the filter of the same filtering characteristic as the optical frequency characteristic of the modulation part

15     output is 0.5, and the detected intensity corresponding to the filter of a filtering characteristic displaced $\pi$ apart from the optical frequency characteristic of the modulation part output is 0; the comparator that compares these detector intensities provides an output of 0.5. For example, in Fig. 42-1, when the modulation part output in the first row is input, the detected

20     intensity of the output light from the filter 231 is 0.5 as shown in the first row, and the detected intensity of the output from the filter 233 is 0 as shown in the third row. Since the detected intensities corresponding to the filters whose filtering characteristics are displaced $\pi/2$ and $3\pi/2$ apart from the optical frequency characteristic of the modulation part output are both 0.25, the

25     comparator that compares the both detected intensities provides an output 0. For example, in Fig. 42-1, the detected intensities of the optical outputs from the filters 232 and 234 are both 0.25 as shown in the second and third rows,

respectively.

[0096] It is desirable that the transmission characteristic of each chip on the optical frequency axis be rectangular, but it is shown in a triangular form for easy distinction of individual chips. In this case, however, since the power at the detector at the time of all the chips passing through the filters is normalized to 1, Embodiment 2-5 operates as described previously without losing generality, irrespective of whether the transmission characteristic is triangular or Gaussian distribution on the optical frequency axis.

In Fig. 40 there is shown only a single combination of the optical transmitter 100 and the optical receiver 200, but when other optical transmitter and optical receiver share the same optical transmission line 330 at the same optical frequency, a different value of L is chosen. L is a multiple of 4 corresponding to the phase shift number M and is a value obtained by dividing the chip number of the optical frequency width FSR by an arbitrary integer n. The value S is a value obtained by dividing L by the phase shift number M, that is, by 4. Letting the number of the phase shift amount be represented by P, P = 0, 1, 2, 3, and P = 0, P = 1, P = 2 and P = 3 correspond to the phase shifts, 0', $\pi/2'$, $\pi'$, and $3\pi/2$, respectively. That is, $2\pi P/M$ (M = 4). Every L chips it is repeated at least n times to provide the transmittance 1 for chips corresponding to the remainders concerning the value L obtained by adding 1 to L/2 to PS which is obtained by multiplying the number P of the phase shift amount by S and the transmittance 0 for the other chips. That is, letting MOD(A, L) represent the remainder of the division of A by L, the transmittance 1 is provided for chips of the chip numbers corresponding to Q changing from 1 through the above-mentioned n in (Q − 1)L + MOD(PS +1, L) to (Q − 1)L + MOD(PS + L/2, L), and the transmittance 0 is provided for the other remaining chips. Since the product of the value L chosen here and

the corresponding value n is constant, an integral of the scalar product of the pseudo-carriers for the interval FSR becomes zero by the differential detection at the receiving side, making it possible to inhibit the input of pseudo-carriers other than those to be received.

5     [0097] As examples of the relations of the above-said values L, M, n, S, P and Q, the chips of the transmittance 1 in the case where n = 1, M = 4, S = 6 and L =24 are shown in gray in Fig. 43(a), and the chips of the transmittance 1 in the case where n = 2, M = 4, S = 3 and L = 12 are shown in Fig. 43(b).

    In the case where the filters used in Embodiment 2-5 are filters that

10     filter pseudo-carriers of optical frequencies outside FSR according to the same functions as those inside FSR and are based on the periodic function of which period is FSR, an integration value of the scalar product of the carriers for the interval FSR becomes zero, and the carriers are orthogonal to each other and hence they do not interfere with each other.   The filters for use in

15     Embodiment 2-5 are such as shown in Fig. 16.

[0098] As described above, according to Embodiment 2-5, since positive- or negative-polarized uncorrelated carriers are emulated by non-polarized intensity modulation which is a part of a repetition of a desired frequency period of broadband light on the optical frequency axis, and since the

20     emulated carriers are phase-modulated, it is possible to implement QPSK with control accuracy lower than that on the order of the wavelength of light.

[Embodiment 2-6]

    As described above with reference to Embodiment 2-5, the QPSK modulation can be emulated by the same scheme as shown in Fig. 35 in which

25     the pseudo-carrier is phase-modulated, in $\pi$-width-chip blocks, to any one of the phase shift positions 0, $\pi/2$, $\pi$, and $3\pi/2$ on the optical frequency (wavelength) axis.   Assuming that the pseudo-carrier for use in this

embodiment is an i-th carrier and that $2\pi f = \Theta$, the filtering characteristic functions of each set are $Ci(\Theta)$ or $Ci(\Theta + \pi)$ and $Ci(\Theta + \pi/2)$ or $Ci(\Theta + 3\pi/2)$; letting $\Sigma$ represent the sum of addition from $h = 0$ to $FSR/\delta\Theta - 1$ over the period FSR where $\Theta = h\delta\Theta$, the following equations hold:

[0099] $\Sigma Ci(\Theta)(Ci(\Theta + \pi/2) - Ci'(\Theta + \pi/2)) = \Sigma Ci(\Theta)(Ci(\Theta + 3\pi/2) - Ci'(\Theta + 3\pi/2)) = 0$ (22)

$$\Sigma Ci(\Theta)(Ci(\Theta) - Ci(\Theta)) = \Sigma Ci(\Theta + \pi)(Ci(\Theta + \pi) - Ci'(\Theta + \pi))$$
(23)

Eqs. (22) and (23) are formulae for digital processing of integrations of Eqs. (20) and (21), respectively.

It will easily be understood that the QAM modulation can be emulated using the pseudo-carriers shown in Embodiment 2-4 and by the same method as described previously with reference to Figs. 37-1 and 37-2. For this QAM modulation, as parenthesized in Figs. 37-1 and 37-2, the optical transmitter 100 uses filters 137a to 137d as substitutes for the filters 133a to 133d, in which case according to two bits of the data set from the signal-to-phase and amplitude converter 111 the modulator 151 selects one of the filters 137a and 137c to control the optical intensity to be either 1 or 3, whereas according to the other two bits in the data set the modulator 152 selects one of the filters 137b and 137d to control the optical intensity to be either 1 or 3. In this instance, the optical receiver 200 needs only to use filters 225 to 228 as substitutes for the filters 221 to 224, and no further modifications are needed. The positions where to dispose modulators 151 and 152 are the same as in the case of Embodiment 2-4. Embodiment 2-6 also produces the same effects as are obtainable with Embodiment 2-6 for the same reasons as in the latter.

[0100] Further, the MPSK modulation can be emulated by using the

pseudo-carrier used in Embodiment 2-5 and phase-modulating it to any one of M arbitrary phase shifts by a $\pi$-width rectangular pattern.

In other words, when the number of phase shifts is M, L which is the number of chips for one period is a multiple of M and a multiple of 2 and

5    takes a value obtained by dividing the total number of chips forming the optical frequency width FSR by n.   With L = MS, it is repeated at least n times every L chips to make those chips 1 (which corresponds to the remainders concerning the value L) of the value obtained by adding 1 to L/2 to PS which is obtained by multiplying S and the number P (P = 0, ..., M $-$ 1;

10    letting one period be represented by $2\pi$, the phase shift amount is expressed as $2\pi P/M$) of the phase shift amount and to make the other chips 0.   That is, setting that the remainder of the division of A by L is Mod(A, L), the chips of the numbers corresponding to Q changing from 1 through the above-mentioned n in (Q $-$ 1)L + Mod(PS + 1, L) to (Q $-$ 1)L + Mod(PS +

15    L/2, L) are made a 1 and the other chips are made a 0.

[0101] Accordingly, letting Ci($\Theta$) and Ck($\Theta$) represent the functions of pseudo-carriers corresponding to i-th and k-th carriers having different values of n (k being a carrier number other than i), respectively, $\Sigma$ represent the summation of addition from h = 0 to FSR/$\delta\Theta$ $-$ 1 over the period FSR where

20    $\Theta$ = h$\delta\Theta$ and P represent a finite value other than zero, the following equation holds:

$$\Sigma(Ci(\Theta)(Ci(\Theta) - Ci'(\Theta)) = P, \Sigma Ck(\Theta)(Ci(\Theta) - Ci'(\Theta)) = 0 \qquad (24)$$

A description will be given below of an example in which the total number of chips forming the optical frequency width FSR is nL = 24 and M =

25    3 in this embodiment.   Since L is a multiple of M and also a multiple of 2 and a measure of 24, L becomes 24 or 12 or 6, n becomes 1, 2, or 4, and S becomes 8, 4, or 2.   Fig. 44 shows the case in which (n, L, M, S) = (1, 24, 3,

8) and (2, 12, 3, 4). The gray color means chips of the transmittance 1. In the case of (n, L, M, S) = (1, 24, 3, 8), since n = 1, there is only Q = 1: for a phase shift 0 (P = 0), the first ((1 − 1)24 + Mod(0 · 8 + 1, 24) = 1) chip a to the 12th ((1 − 1)24 + Mod(0 · 8 + 24/2, 24) = 12) chip b have the

5  transmittance 1 as shown in the left-hand diagram of Fig. 44(a); for a phase shift 2π·(1/3) (P = 1), the ninth ((1 − 1)24 + Mod(1 · 8 + 1, 24) = 9) chip a to 20th ((1 − 1)24 + Mod(1 · 8 + 24/2, 24) = 20) chip b have the transmittance 1 as shown in the left-hand diagram of Fig. 44(c); and, for a phase shift 2π·(2/3) (P = 2), the 17th ((1 − 1)24 + Mod(2 · 8+1, 24) = 17) chip a to the fourth ((1 −

10  1)24 + Mod(2 · 8 + 24/2, 24) = 4) chip b have the transmittance 1 as shown in the left-hand diagram of Fig. 44(c). That is, since the maximum chip number is 24, the first to fourth chips and the 17th to 24th chips go to 1s. [0102] In the case of (n, L, M, S) = (2, 12, 3, 4), since n = 2, there are Q = 1 and Q = 2. As shown in the right-hand diagrams of Figs. 44(a) to 44(d): in

15  the case of the phase shift P = 0, for Q = 1, the first ((1 − 1)12 + Mod(0 · 4 + 1, 12) = 1) chip a to the sixth ((1 − 1)12 + Mod(0 · 4 + 12/2, 12) = 6) chip b are made 1's, and for Q = 2,the 13th ((2 − 1)12 + Mod(0 · 4 + 1, 12) = 13) chip c to the 18th ((2 − 1)12 + Mod(0 · 4 + 12/2, 12) = 18) chip d are made 1's ; in the case of the phase shift 2π·(1/3) (P = 1), for Q = 1, the fifth ((1 − 1)12 +

20  Mod(1 · 4 + 1, 12) = 5) chip a to the 10th ((1 − 1)12 + Mod(1 · 4 + 12/2, 12) = 10) chip b are made 1's, and for Q = 2, the 17th ((2 − 1)12 + Mod(1 · 4 + 1, 12) = 17) chip c to the 22nd ((2 − 1)12 + Mod(1 · 4 + 12/2, 12) = 22) chip d are made 1's; and in the case of the phase shift 2π·(2/3) (P = 2), for Q = 1, the first to second chips and the ninth to 12th chips are made 1's, and for Q = 2,

25  the 13th to 14th chips are made 1's and the 21st to 24th chips are made 1's. That is, for Q = 1, the ninth ((1 − 1)12 + Mod(2 · 4 + 1, 12) = 9) chip a to the second ((1 − 1)12 + Mod(2 · 4 + 12/2, 12) = 2) chip b are made 1's, and for Q

= 2, the 21st $((2 - 1)12 + Mod(2 \cdot 4 + 1, 12) = 21)$ chip c to the 14th $((2 -$
$1)12 + Mod(2 \cdot 4 + 12/2, 12) = 14)$ chip d are made 1's.   In this instance, for
$Q = 1$, the range over which the chip 1 can be shifted is from the first to 12th
chip position, whereas for $Q = 2$ it is the range from the 13th to 24th chip

5    positions.   In this embodiment, too, as will be evident from Fig. 44, even if
other signals having different values of n are received, the interference
between pseudo-carriers is cancelled at the receiving side, and hence they can
be received independently of each other.

[0103] The filter of the optical transmitter according to this embodiment is

10    provided with three 0-, $2\pi/3$- and $4\pi/3$-phase filters in place of the four 0-, $\pi$-,
$\pi/2$- and $3\pi/2$-phase filters forming the filter 131 in Fig. 2-5.   Instead of
using the four 0-, $\pi$-, $\pi/2$- and $3\pi/2$-phase filters and two sets of comparators
for comparing the outputs from detectors connected to the four filters whose
phase shift amounts differ in steps of $\pi$, the optical transmitter of this

15    embodiment is provided with the three 0-, $2\pi/3$- and $4\pi/3$-phase filters, three
$\pi$-, $5\pi/3$- and $\pi/3$-phase filters, three $\pi$-, $5\pi/3$- and $\pi/3$-phase filters whose
phase shift amounts differ by $\pi$ from them, respectively, and three sets of
comparators for comparing outputs from detectors connected to the filters
whose phase shift amounts differ in steps of $\pi$.

20    [0104] As described above, positive- or negative-polarized uncorrelated
carriers are emulated by non-polarized intensity modulation which is a part of
a repetition of a desired frequency period of broadband light on the optical
frequency axis, and the emulated carriers are phase-modulated; by this, it is
possible to implement MPSK with control accuracy lower than that on the

25    order of the wavelength of light.

[Embodiment 2-7]

The $\pi$-phase filter 133c (137c) and $3\pi/2$-phase filter 133d (137d) in

the optical transmitter 100 shown in Fig. 37-1 are omitted, the switches 151a
and 152a in the modulators 151 and 152 are omitted accordingly, the 0-phase
filter 133a (137a) and the π/2-phase filter 133b (137b) are connected to the
amplitude changing parts 151b and 152b in the modulators 151 and 152,

5    respectively, and the signal-to-phase and amplitude converter 111 is replaced
with a signal-to-amplitude converter 112, that is, with the serial-parallel
converter 110a in the signal-to-phase converter 110a shown in Fig. 30, by
which the one bit (data) and the other bit (data) of a two-piece data set are
made to correspond to the modulators 151 and 152 to effect control such that

10   the optical intensity is a 3 or 1 depending on the bit 0 or 1.   In the optical
receiver 200, the code converter 260 provides data 0 or 1, depending on
whether the output intensities of the comparators 241 and 242 are 3s or 1s,
and outputs the pieces of data in serial form.

[0105] With such an arrangement, QAM modulation, which has four signal

15   points in the first quadrant as depicted in Fig. 38(a), can be performed not
only for the pseudo-carriers based on the trigonometric function on the optical
frequency (wavelength) axis described previously with reference to
Embodiment 2-4 but also for the rectangular pattern pseudo carriers on the
optical frequency (wavelength) axis described above with reference to

20   Embodiment 2-6.

Such QAM modulation with four signal points can be achieved as
QAM modulation which has four signal points in any one of the second, third
and fourth quadrants in Fig. 38(a), by use of two filters selected from among
combinations of 133b (137b) and 133c (137c), 133c (137c) and 133d (137d)

25   and 133a (137a) and 133d (137d).   In these cases, when the outputs from the
comparators 241 and 242 are negative, they are converted to data 0 or 1,
depending on whether their absolute values are 3s or 1s.

[Embodiment 2-8]

Embodiment 2-8 according to the second mode of working of the invention uses a plurality of light sources each of which emits light of an optical frequency characteristic function of a different phase.   Referring now to Fig. 45, the optical transmitter of Embodiment 2-8 will be described below in connection with the case where L = 4S.   In Embodiment 2-8, FSR/n on the optical frequency axis, where n = 1, that is, FSR is one period, and multiple light sources which provide, in each period, 2S-chip optical outputs at the 0-, $\pi/2$-, $\pi$- and $3\pi/2$-phase shift positions on the optical frequency axis, respectively, are used to permit implementation of the QPSK or QAM modulation according to Embodiment 2-5 or Embodiment 2-6.

[0106] The Fig. 45 example uses two sets of light sources each of which emits light of an S-chip optical frequency and the optical output intensity of each light source can be controlled; the illustrated example is provided with a total of L/S sets of light sources (each set of which is formed by a single broadband light source of a 2S optical frequency width, or 2S light sources) which is twice larger than L/2S.

Of the L/S sets of light sources, L/2S sets of light sources, each emitting light of the S-chip optical frequency, are used to simulate a 0-phase or $\pi$-phase carrier.   That is, as Fig. 46 shows S-chip output light of each of the phases 0, $\pi/2$, $\pi$ and $3\pi/2$, the output light from a light source 120a which outputs S chips of the first continuous optical frequency in each period, that is, 0-phase S chips, and the output light from a light source 120b which outputs the next S chips, that is, $\pi/2$-phase S chips, are used to emulate the 0-phase carrier; and the output light from a light source 120c which outputs the next S chips, that is, $\pi$-phase S chips, and the output light from a light source 120d which outputs the next S chips, that is, $3\pi/2$-phase S chips, are used to

emulate the $\pi$-phase carrier.    The remaining L/2S light sources are used to emulate the $\pi/2$-phase carrier or $3\pi/2$-phase carrier.    That is, the output light from a light source 120e which outputs the S chips succeeding the first S chips in each period on the optical frequency axis, that is, $\pi/2$-phase S chips,

5    and the output light from a light source 120f which outputs the next S chips, that is, $\pi$-phase S chips, are used to emulate the $\pi/2$-phase carrier; and the output light from a light source 120g which outputs the next S chips, that is, $3\pi/2$-phase S chips, and the output light from a light source 120h which outputs the next S chips, that is, 0-phase S chips, are used to emulate the

10    $3\pi/2$-phase carrier.    These 0-phase, $\pi/2$- phase, $\pi$-phase and $3\pi/2$-phase carriers correspond to the transmitted light of P = 0, P = 1, P = 2 and P = 3 in Fig. 43(a), respectively.

[0107] The above description has been given of the example in which n = 1, but when n is an integer equal to or greater than 2, the value of S

15    corresponding to n in the order of optical frequency needs only to be allocated in S-chip blocks to the 0-phase light source, the $\pi/2$-phase light source, the $\pi$-phase light source and the $3\pi/2$-phase light source.    The value n that can be used is determined by the relation to the chip number L that corresponds to one period obtained by dividing the optical frequency width FSR by n.    In

20    the cases where FSR = 24, n = 2, L = 24/2 = 12 and S = 12/4 = 3, light of the 0-phase, $\pi/2$-phase, $\pi$-phase ad $3\pi/2$-phase pseudo-carriers becomes the same as the transmitted light for P = 0, P = 1, P = 2 and P = 3 in Fig. 43(b).    The value L is a multiple of 4 corresponding to the number M of phase shifts, and the value S is a value obtained by dividing the value L by the number M of

25    phase shifts that is, by 4 (L = 4S).    Every L chips it is repeated at least n times to turn ON (1) the light sources for chips corresponding to the remainders concerning the value L of the value obtained by adding 1 to L/2 to

PS which is obtained by multiplying the number P of the phase shift amount
(P = 0, 1, 2, 3) by S and turn OFF (0) the light sources for the other chips.
That is, letting MOD(A, L) represent the remainder of the division of A by L,
the light sources (two sets in this example) for the chips of the chip numbers

5     corresponding to Q changing from 1 ~~to~~ through the above-mentioned n in (Q
− 1)L + MOD(PS +1, L) to (Q − 1)L + MOD(PS + L/2, L) are turned ON (1)
and the light sources for the other remaining chips are turned OFF (0).

[0108] Fig. 45 illustrates the optical transmitter intended to emulate the QAM
modulation shown in Fig. 38(a), in which the transmission signal (data)

10     sequence from the terminal 101 is converted to four sequences by the
serial-parallel converter 110C in a signal-to-phase and amplitude converter
113.     The third significant data (bit) in each 4-bit data set (the data array in
the serial-parallel converter 110c being the same as the order of bits for each
data set shown in Fig. 38(a)) is used to control the switch 153a; when the data

15     value is 0, a register (drive signal generating part) 153b having stored therein
the value 3 is connected to a switch 153d; when the data value is 1 and a
register (drive signal generating part) 153c having stored therein the value 1 is
connected to the switch 153d; the switch 153d is controlled by the most
significant data (bit); when the data value is 0, the switch 153a is connected to

20     the 0-phase light source 120a and the $\pi/2$-phase light source 120b, and light of
the intensity 3 is output from the both light sources 120a and 120b, that is,
light of the 0-phase pseudo-carrier is output with the intensity 3; and when the
most significant data (bit) value is 1, the switch 153a is connected to the
$\pi$-phase light source 120c and the $3\pi/2$-phase light source 120d, and light of

25     the intensity 1 is output from the both light sources 120c and 120d, that is,
light of the $\pi$-phase pseudo-carrier is output with the intensity 1.

[0109] A switch 154a is controlled by the least significant data (bit) in the data

set; when the data value is 0, a register 154b having stored therein the value 3 is connected to a switch 154d; when the data value is 1, a register 154c having stored therein the value 1 is connected to the switch 154d; the switch 154d is controlled by the second significant data (bit) of the data set; when the data value is 0, the switch 154a is connected to the $\pi/2$-phase light source 120e and the $\pi$-phase light source 120f, and light of the intensity 3 is output from the both light sources 120e and 120f, that is, light of the $\pi/2$-phase pseudo-carrier is output with the intensity 3; and when the data value is 1, the witch 154a is connected to the $3\pi/2$-phase light source 120g and the 0-phase light source 120h, and light of the intensity 1 is output from the both light sources 120g and 120h, that is, light of the $3\pi/2$-phase pseudo-carrier is output with the intensity 1.

[0110] It will easily be understood that thus the optical transmitter according to this embodiment can also output an optical QAM modulated signal similar to that obtainable with the optical transmitter 100 of Embodiment 2-6 described previously with reference to Fig. 37. Accordingly, the optical receiver 200 for use in this case may be the same as shown in Fig. 36. In the optical receiver depicted in Fig. 45 the light sources need only direct modulation; for example, in the case of using laser light sources, their direct modulation is performed by controlling the magnitude of their drive current--this dispenses with the expensive phase and amplitude modulation part 150 composed of filters and modulations such as employed in Embodiment 2-6.

With this embodiment, too, the QPSK modulation can similarly be done as described previously with reference to Embodiment 2-3 by omitting the switches 153d and 154d in Fig. 45, and connecting the registers 153b and 154b directly to the switches 153d and 154d, respectively, to control the

switches 153d and 154d by each piece of data of the two-data set of the signal-to-amplitude modulator 112 in Fig. 6. Further, the QAM modulation described previously with reference to Embodiment 2-7 can also be achieved by: omitting the switches 153d and 154d are omitted; connecting the switches

5    153a and 154a to two sets of light sources (a total of four light sources) that output light of mutually orthogonal pseudo-carriers; and controlling the switches 153a and 154a as referred to previously in connection with Embodiment 2-7. Incidentally, in the example in which the switches 153a and 154a are omitted and in the example in which the switches 153d and 154d

10    are omitted, the serial-parallel converter 110C is substituted with the serial-parallel converter 110a of the signal-to-phase converter 110 in Fig. 30.

[0111] The QAM modulation can also be implemented by use of two light sources whose phase shift amounts differ by $\pi/2$, for example, the 0-phase shift light source and the $\pi/2$-phase chip light source. In this instance, since

15    the phase is one-half that in the QAM modulation by the embodiment described above with respect to Fig. 45, doubling the number of steps for intensity modulation control in the Fig. 45 embodiment enables signal transmission to be achieved at the same level as that by the embodiment. Additionally, the number of light sources used can be reduced by half.

20    It is also possible to perform, by use of multiple light sources, the same modulation as the MPSK modulation in which the number of phase shift positions is an arbitrary value M as described previously with respect to Embodiment 2-6. Referring to Fig. 45, this example will be described in connection with the case where $M = 4$. In this instance, the signal-to-phase

25    and amplitude converter 113 in Fig. 45 is replaced with the signal-to-phase converter 110 in Fig. 30. And multiple light sources are used which provide, in each period FSR/n, 2S-chip optical outputs at the 0-, $\pi/2$-, $\pi$- and

$3\pi/2$-phase shift positions on the optical frequency axis, respectively. Since $M = 4$, the pseudo-carrier corresponding to each phase shift is the same as in the embodiment described above with reference to Fig. 45, and in accordance with the output from the signal-to-phase converter 110: light of the intensity 1

5  is output from the 0-phase chip light source corresponding to the 0-shift amount and the $\pi/2$-phase chip light source; light of the intensity 1 is output from the $\pi/2$-phase chip light source corresponding to the $\pi/2$-shift amount and the $\pi$-phase chip light source; light of the intensity 1 is output from the $\pi$-phase chip light source corresponding to the $\pi$-shift amount and the

10  $3\pi/2$-phase chip light source; or light of the intensity 1 is output from the 0-phase chip light source corresponding to $3\pi/2$-shift amount and the $3\pi/2$-phase chip light source.

[0112] In this way, the MPSK modulation can be achieved without using an expensive phase modulation part composed of filters and modulators.

15  The Fig. 45 embodiment uses two S-chip light sources so as to output light of one pseudo-carrier. The two light sources can be replaced with one 2S-chip light source. In this instance, however, four kinds of relatively broadband 2S-chip light sources are used as is evident from Fig. 45. With such an arrangement as depicted in Fig. 45, however, it is true that the number

20  of kinds of light sources is four, but the optical frequency width of each light source is S-chip, permitting appreciable reduction in the manufacturing cost as compared with that in the case of using 2S-chip light sources. The QPSK modulation can also be performed by use of the four kinds of S-chip light sources. In the Fig. 45 embodiment, 4n carriers are required for each of the

25  emulation of the 0-phase or $\pi$-phase carrier and the emulation of the $\pi/2$-phase or $3\pi/2$-phase carrier, and for the carrier of each phase, two S-chip light sources are used, that is, the number of light sources used is a total of $2 \times 4n$.

The two light sources for outputting carriers at the same optical frequency is substituted with one light source which emits light with an intensity of the combined output of the carriers 1 or 0. That is, in the case of Fig. 45, letting "1" represent those of the 0-phase chip light source, the $\pi/2$-phase chip light

5 source, $\pi$-phase chip light source and the $3\pi/2$-phase chip light source (Each light source is an S-chip light source, but for the sake of brevity, it is referred to as a chip light source, omitting "S.") which emit light of the intensity 1 for the carrier of each phase and letting "0" represent the light sources which do not emit light, the output from each chip light source is as listed below.

10 [0113] 0-phase carrier:

(0-phase chip light source, $\pi/2$-phase chip light source, $\pi$-phase chip light source, $3\pi/2$-phase chip light source) = (1100)

$\pi/2$-phase carrier:

(0-phase chip light source, $\pi/2$-phase chip light source, $\pi$-phase chip

15 light source, $3\pi/2$-phase chip light source) = (0110)

$\pi$-phase carrier:

(0-phase chip light source, $\pi/2$-phase chip light source, $\pi$-phase chip light source, $3\pi/2$-phase chip light source) = (0011)

$3\pi/2$-phase carrier:

20 (0-phase chip light source, $\pi/2$-phase chip light source, $\pi$-phase chip light source, $3\pi/2$-phase chip light source) = (1001)

Since light of two carriers in orthogonal relationship is output, those of these optical outputs which are emitted from the chip light sources of the same phase are combined, and hence the intensity of the combined light goes

25 to a 2. Accordingly, by pre-doubling the intensity of the output light from light source whose optical outputs are combined, it is possible to output light of four carriers through use of one light source for each of four kinds of

S-chip light sources.    The output from each chip light source is as follows:

0-phase carrier + π/2-phase carrier:

(0-phase chip light source, π/2-phase chip light source, π-phase chip light source, 3π/2-phase chip light source) = (1210)

5        0-phase carrier + 3π/2-phase carrier:

(0-phase chip light source, π/2-phase chip light source, π-phase chip light source, 3π/2-phase chip light source) = (2101)

π-phase carrier + π/2-phase carrier:

(0-phase chip light source, π/2-phase chip light source, π-phase chip

10    light source, 3π/2-phase chip light source) = (0121)

π-phase carrier + 3π/2-phase carrier:

(0-phase chip light source, π/2-phase chip light source, π-phase chip light source, 3π/2-phase chip light source) = (1012)

Such a reduction of the number of light sources is applicable as well to

15    the MPSK modulation using multiple light sources as referred to previously.

[0114] In the manner described above, the number of light sources can be reduced by half as compared with that needed in the Fig. 45 embodiment and the step intervals for intensity modulation control can be made larger than in the afore-mentioned QAM modulation in which the number of light sources is

20    smaller than in the case of Fig. 45--this produces the effect of robustness against the influence of noise.

[Embodiment 2-9]

Embodiment 2-9 includes the above-described embodiments and makes the pseudo-carrier more generalized, and this example is an application

25    to the QAM modulation.    Referring to Fig. 47, an example of the communications system according o this embodiment will be described below.

[0115] The optical transmitter 100 is provided with a set of i- and i'-th filters 161 and 161' and a set of j- and j'-th filters 162 and 162'. These filters 161, 161' and 162, 162' perform filtering of at least the optical frequency width FSR at the optical frequency (wavelength) of light that the light source 120 emits. Assuming that the optical frequency is an optical frequency spaced from the reference optical frequency fs (= C/$\lambda$s, where C is light velocity), that is, normalized by the reference optical frequency (It can be said that the filter function is a parameter representing phase.), the value $C_i(f)$ of the filtering characteristic function of the i-th filter 161 in the phase f, which is one of the two filters of the first-mentioned set, and the value $C_{i'}(f)$ of the filtering characteristic function of the i'-th filter 161' in the phase f, which pairs with the i-th filter 161, are complementary to each other; hence, they bear the same relation as that of Eq. (4).

[0116]  $C_i(f) + C_{i'}(f) = 1$  (4)

The j-th filter 162 and the j'-th filter 162' of the other set also bear a similar relation. The characteristic functions of the filters 161, 161', 162 and 162' constitute the afore-mentioned pseudo-carriers.

The optical receiver 200 according to Embodiment 2-9 is identical in construction to the optical receiver 200 in Fig. 37 except that the filters used differ from those used in the latter. The optical receiver of this embodiment uses filters of the same filtering characteristics of the filters used in the optical transmitter, that is, an i-th filter 271 identical in filtering characteristic to the i-th filter 161, an i'-th filter 271' identical in filtering characteristic to the i'-th filter 161', and j-th and j'-th filters 272 and 272' identical in filtering characteristic to the j-th and j'-th filters 162 and 162', respectively.

[0117] With such an arrangement, the comparator 241 compares the detected optical intensity corresponding to the transmitted light through the i-th filter

271 and the detected optical intensity of the transmitted light through the i'-th filter 271', and, assuming the value Di(f) at the normalized optical frequency f, the output from the comparator 241 is given by Eq. (3) in the first mode of working of the invention.

5 $$Di(f) = Ci(f) - Ci'(f) \qquad (3)$$

By the detector 231 respective optical frequency components of the transmitted light through the i-th filter are detected as the optical intensity of the transmitted light as a whole. The same goes for the other detectors. Accordingly, the integration value of the scalar product of the filtering

10 characteristic function Ci(f) of the i-th filter 161 of the transmitting side at the normalized optical frequency f and the filtering characteristic function Di(f) of the i-th filter 271 of the receiving side at the normalized optical frequency f over the continuous optical frequency range FSR in which to perform filtering by the i-th filter 271 is a non-zero finite value, and the relation of the

15 following equation (5)' holds.

[0118] $$\int Ci(f) \, Di(f) \, df = P \qquad (5)'$$

Eq. (5) corresponds to a generalized version of Eq. (5) shown in the first mode of working of the invention.

The integration value of the scalar product of the filtering

20 characteristic function Ci(f) of the i-th filter in the phase f and the filtering characteristic function Dj(f) of an j-th filter other than the i-th one at the normalized optical frequency f over the continuous optical frequency range FSR contained in the optical frequency range which is filtered by the filter is zero, and Eq. (6) mentioned in the first mode of working of the invention

25 holds.

$$\int Ci(f) \, Dj(f) \, df = 0 \qquad (6)$$

Accordingly, optical components having passed through the j-th filter

are not contained in the comparator output which is provided by subtracting the output of a detector 231' for detecting the intensity of transmitted light through the i'-th filter 271' from the output of the detector 231 for detecting the intensity of transmitted light through the i-th filter 271. Thus,

5    Embodiment 2-9 enables the receiving side to cancel the input from the other pseudo-carriers except the target pseudo-carrier for receiving by differential detection.

[0119] Furthermore, the filtering characteristic function of the i-th filter 161 is a periodic function with the optical frequency as a variable, and it is

10   preferable that the transmittance (value) $C_i(f)$ at the normalized optical frequency f repeat in the period at intervals of $FSR_i$ (= FSR/n) = $\Lambda$) so that Eq. (1) mentioned in the first mode of working of the invention holds.

$$C_i(f) = C_i(f + FSR_i) \qquad\qquad (1)$$

With such an arrangement, the receiving side is allowed to cancel, by

15   differential detection, the input from the other pseudo-carriers except the target pseudo-carrier for receiving not depending on the differences in optical frequency and in the reference optical frequency fs for each light source. In this way, Embodiment 2-9 implements QAM with control accuracy lower than that on the order of optical wavelength. It will be understood that Eqs.

20   (1), (3) to (5)' hold for both of the pseudo-carriers based on the trigonometric function used in Embodiments 2-1 to 2-4 and 2-7 and the chip-structured pseudo-carriers used in Embodiments 2-5 to 2-8. Incidentally, in the case of the chip-structured pseudo-carriers, $\int d\Theta$ is replaced with $\Sigma$ in the equations. Further, it will be seen that the integral over an interval from an arbitrary

25   value f to f + FSR in the optical frequency region for filtering by the filter is a value obtained by dividing FSR by 2, allowing that Eq. (2) in the first mode of working of the invention also holds.

[0120]  $\int C_i(f)df = FSR/2$  (2)

The 0-phase and $\pi$-phase pseudo-carriers in Embodiments 2-1 to 2-8 correspond to the i-th and i'-th pseudo-carriers in Embodiment 2-9, respectively, and the $\pi/2$-phase and $3\pi/2$-phase pseudo-carriers correspond to

5    the j-th and j'-th pseudo-carriers in Embodiment 2-9, respectively.   That is, Embodiment 2-9 indicates general characteristics of the pseudo-carriers in the present invention, and it can be said that the other embodiments are specialized versions of Embodiment 2-9.

[Embodiment 12-10]

10    A description will be given below of another example that employs the chip-structured pseudo-carriers.   In Fig. 47, the filters 161' and 162' are omitted and the signal-to-phase and amplitude converter 111 is substituted with a signal-to-amplitude converter 112 as parenthesized.   The other parts remain unchanged but the filtering characteristics of the filters 161 and 162

15    are adjusted as mentioned below.

[0121] The number of chips which, upon receiving light from the light source, the i-th filter 161 of the optical transmitter and the j-th filter 162 of the optical transmitter other than the i-th filter or of a different optical transmitter sharing the same transmission line turn ON (pass) at the same time in the optical

20    frequency region FSR/n (n = integer equal to or greater than 1) for filtering by the i-th filter 161 and in the optical frequency region FSR for filtering by the filter 162 and the numbers of chips which the i-th filter 161 of the optical transmitter turns ON (pass) in its filtering optical frequency region FSR and the j-th filter 162 of the optical transmitter other than the i-th filter or of a

25    different optical transmitter sharing the same transmission line turns OFF (not pass) in its filtering optical frequency region FSR are equal to each other.   In other words, the number of chips which the i-th filter 161 and the j-th filter

162 turn On at the same time (at the same chip positions) and the number of chips which at the same chip positions, the i-th filter 161 turns ON and the j-th filter 162 turns OFF are equal to each other.

[0122] Accordingly, letting $Ci(\Theta)$, where $\Theta = 2\pi f$, represent the value of an

5   i-th carrier for a chip of a phase $\Theta$ corresponding to the wavelength difference (frequency difference) from the reference wavelength (the reference frequency), $Ci(\Theta) = Ci(\Theta + FSR/n)$; letting $Ci'(\Theta) = 1 - Ci(\Theta)$, $\Sigma Ci(\Theta)(Ci(\Theta) - Ci'(\Theta))$ (where $\Sigma$ is the summation of addition from $h = 0$ to $FSR/\delta\Theta - 1$ over the period FSR where $\Theta = h\delta\Theta$) is a finite value; letting $Ck(\Theta)$ represent

10   the in-phase-$\Theta$ intensity of the function indicating a k-th carrier other than the i-th carrier (where k is the pseudo-carrier number of other than i), the relation $\Sigma Ck(\Theta)(Ci(\Theta) - Ci'(\Theta)) = 0$ (where $\Sigma$ is the summation of addition from $h = 0$ to $FSR/\delta\Theta - 1$ over the period FSR where $\Theta = h\delta\Theta$) holds ; letting $Cj(\Theta)$ represent the in-phase-$\Theta$ intensity of the function indicating a j-th carrier,

15   $Cj(\Theta) = Cj(\Theta + FSR/n)$; letting $Cj'(\Theta) = 1 - Cj(\Theta)$, $\Sigma Cj(\Theta)(Cj(\Theta) - Cj'(\Theta))$ (where $\Sigma$ is the summation of addition from $h = 0$ to $FSR/\delta\Theta - 1$ over the period FSR where $\Theta = h\delta\Theta$) is a finite value; and letting $Cm(\Theta)$ the in-phase-$\Theta$ intensity of the function indicating an m-th carrier other than the j-th carrier (where m is the pseudo-carrier number other than i),

20   $\Sigma Cm(\Theta)(Cj(\Theta) - Cj'(\Theta))$ (where $\Sigma$ is the summation of addition from $h = 0$ to $FSR/\delta\Theta - 1$ over the period FSR where $\Theta = h\delta\Theta$) holds.

[0123] The optical receiver 200 used in this embodiment is the same as that described previously with reference to Embodiment 2-7.   In this way, QAM can be implemented.   In Embodiment 2-10, too, equations that have $\int d\Theta$

25   replaced with $\Sigma$ in Eqs. (1) to (4) hold.   As the filter for use in this embodiment, it is possible to use a filter which provides transmittance 1/ transmittance 0, in accordance with the value of one bit forming the

Hadamard code, for chips of the number derived from the division of the chip number corresponding to FSR/n, for instance, by the code length of the Hadamard code. Moreover, in the case of using a filter which filters optical frequencies in the region equal to or wider than FSR in correspondence to a

5     code that is a continuous concatenation of Hadamard codes, equations that have $\int d\Theta$ replaced with $\Sigma$ in Eqs. (1) to (5) hold in an arbitrary optical frequency region FSR.

[0124] A description will be given below of a concrete example which uses another code in Embodiment 2-10. A sequence in which filter ON and OFF

10     chips are 1s and 0s, respectively, corresponds to the longest sequence in which L is the code length (period length). For example, in the case of L = 3, the sequence through which the first filter 161 can be made (101). In this instance, the sequences through the other filters (second and third filters) can be made (011) and (110), respectively, shifted from the sequence through the

15     first filter 161.

The optical receiver 200 is provided with: an i-th filter 271 which transmits therethrough light of ON-chips contained in the optical frequency filtered by the i-th filter 161 at the transmitting side; an i'-th filter 271' which transmits therethrough light of OFF-chips contained in the optical frequency

20     filtered by the i-th filter 161; a first detector group (231, 132) for detecting the optical intensity of light transmitted through each of first filters (271, 272); a second detector group (233, 234) for detecting the optical intensity of light transmitted through each of second filters (271', 272'); a comparator group (241, 242) for comparing the optical intensities by subtracting the intensity

25     detected by the second detector from the intensity detected by the first detector; and an amplitude-signal converter (260) by which a combination of amplitudes modulated by modulators of the corresponding transmitting station,

output from the comparator group, is converted to the transmission signal.

[0125] Consider, as an example of operation, the comparator output intensity in the case of receiving the signal (101) from the transmitter provided with the i-th filter 161 by th receiver corresponding thereto and the comparator output

5 intensity in the case of receiving the signal (011) corresponding to the j-th filter 162. The output from the detector 231, which detects the optical intensity of the output light from the i-th filter 271 of the receiver, corresponding to the i-th filter 161, which permits the passage therethrough of the ON-chip light, is a two-chip component in the signal (101); the chip of the

10 signal (101) which passes through the i'-th filter 171' of (010) filtering characteristics is 0; the output from the detector 233, which detects the optical intensity of the output light from the j'-th filter 272', is 0; and the output from the comparator 241 for comparing optical intensities by subtracting the intensity detected by the detector 233 from the intensity detected by the

15 detector 231 is a two-chip output.

[0126] It is only one chip that received light (1019 passes through a j-th filter 272 for selecting signal light (011) which corresponds to the j-th filter 162 at the transmitting side, the output from the detector 232 for detecting the optical intensity of light transmitted through the j-th filter 272 is a one-chip output,

20 the output from the detector 234 for detecting the intensity of light transmitted through a j'-th filter for selecting the light of an OFF-chip of the signal light (011) is a one-chip output, and the output from the comparator 242 for comparing the intensity detected by the detector 232 and the intensity detected by the detector 234 by subtracting the latter from the former is a

25 0-chip output.

[0127] As described above, this embodiment also enables the receiving side to cancel the input from the other pseudo-carriers except the target

pseudo-carrier for receiving by differential detection as in Embodiment 2-7, permitting implementation of QAM with control accuracy lower than that on the order of optical wavelength. In the conventional optical communication method of the type that controls the phase of the optical signal, it is necessary

5    to control the phase of a single-wavelength (frequency) optical signal with accuracies on the order of tens of nanometers which is a few tenth of micrometer for the optical wavelength and hence is sufficiently accurate; at present such phase control is feasible experimentally, but from the economical point of view its realization is difficult, and the optical communications

10    system that involve QPSK, QAM or similar phase modulation has not been put to practical use yet.

[0128] According to the second mode of working of the invention, however, it is relatively easy to perform MPSK or QAM for optical carriers in the frequency domain.

15        It will be seen that in Embodiment 2-10, too, equations with $\int d\Theta$ replaced by $\Sigma$ in Eqs. (1) to (4) holds in a predetermined period FSR. Accordingly, assuming that the pseudo-carrier has a rectangular pattern periodic function composed of the chip of intensity 1 and the chip of intensity 0 in the region FSR, the number of chips of the i-th and j-th carriers

20    corresponding to the filtering characteristics of the i-th filters 161, 271 and the j-th filters 162, 272 that have the intensity 1 (or intensity 0) at the same optical frequency positions and the number of chips of the i-th carrier that have the intensity 1 (or intensity 0) and the intensity 0 (or intensity 1) at the same optical frequency positions, respectively, are equal to each other. The

25    rectangular pattern periodic function can also be applied to the case of using the light sources each corresponding to one chip as shown in Embodiment 2-8.

[0129] In the QAM modulation in each of the embodiments described above, either the intensity 1 or 3 is chosen by third and fourth parameters, respectively, to express any one of combinations of four pieces of data 1 and 0, that is, any one of 16 data combinations, but provision may be made to

5 provide any one of 17 or more combinations.   That is, the optical transmitter needs only to effect selective control, in accordance with the number of combinations of pieces of data 1 and 0 desired to express, so that the light corresponding to the i-th (or i'-th) and j-th (or j'-th) carriers may have the optical intensity of any one of predetermined multiple values.   The optical

10 receiver needs only to control the code-signal converter 260 to output that one of possible combinations of four or more pieces of data 0 or data 1 which corresponds to each possible combination for any one of predetermined multiple digital values including pieces of polarized information from the A/D converters 261 and 262 in Fig. 37-2.

15 [0130] Any one of the predetermined multiple digital values from the A/D converters 262 and 264 may sometimes include the polarized information and sometimes may not.   The latter case corresponds to the case in which signal points only in one quadrant in Fig. 38(a), for example, in the first quadrant as referred to previously in connection with Embodiment 2-7, for instance, and

20 the output from the code-signal converter 260 is converted to one of possible combinations of two pieces of data; accordingly, when the polarized information is contained as a digital value in the outputs from the A/D converters 263 and 264, the code-signal converter output is a combination of two or more pieces of data.   Accordingly, it can be said that any one of

25 multiple values corresponds, in general, to a combination of two or more pieces of data.

[Embodiment 2-11]

Figs. 48-1 and 48-2 illustrate a communications system according to Embodiment 2-11 of the present invention. In the optical transmitter 100, K (K being an integer equal to or greater than 2) optical transmitters 100, described previously with respect to Embodiment 2-3 depicted in Fig. 35, are

5  accommodated in parallel as indicated by $100_1$, ..., $100_K$ in Fig. 48-1; the transmission signal (data sequence) from the input terminal 101 is converted by a serial-parallel converter 170 to K parallel sequences, which are input to the signal-phase converters 110 of the optical transmitters $100_1$, ..., $100_K$, respectively. The outputs from the optical transmitters $100_1$, ..., $100_K$ are

10  combined by a combiner 171, from which the multiplexed output is provided to the optical transmission line 300.

[0131] In the optical receiver 200, K optical transmitters 100, described for use in Embodiment 2-3, that is, depicted in Fig. 30, are disposed in parallel as indicated by $200_1$, ..., $200_K$ in Fig. 48-2; the optical signal from the optical

15  transmission line 300 is split by a splitter 270 into K optical signals, which are input to the splitter 210 of the optical receivers $200_1$, ..., $200_K$, respectively. The output signals from the optical receivers $200_1$, ..., $200_K$ are converted by a parallel-serial converter 273 to the original transmission signal.

The optical transmitters $100_1$, ..., $100_K$ and the optical receivers $200_1$

20  ..., $200_K$ performs transmission and reception without interference with each other as described previously with reference to Embodiment 2-3.

[0132] The optical transmitters $100_1$, ..., $100_K$ and the optical receivers $200_1$, ..., $200_K$ in this embodiment employ filters of the type that when a predetermined period is used as a reference period, the period of a

25  trigonometric function contained in the filtering characteristic of each filter is a period obtained by dividing the reference period by a natural number. That is, the above-mentioned reference period and the period of each filter of the

optical transmitters $100_1$, ..., $100_K$ correspond to a pair of fundamental and multiple periods generated by Fourier transform. For example, assuming that the value of the number N for dividing FSR is in the range of 1 to K, these FSR, FSR/2, ..., FSR/K are in the optical transmitters $100_1$, $100_2$, ..., $100_K$, respectively, and their optical signals are combined by the combiner 171 into a combined optical signal, which is equivalent to a signal subjected to inverse discrete Fourier transform processing.

[0133] Let the periods of filtering characteristic functions of the filters for use in the optical receiver 200 be represented. Such relationships provide an operation equivalent to that by which the received optical signal is split into optical signals and they are discrete-Fourier-transformed by the optical receivers $200_1$, ..., $200_K$ into the original transmission signal.

In this way, according to Embodiment 2-11, it is possible to implement pseudo OFDM (Orthogonal Frequency Division Multiplex) by use of multiple pseudo-carriers compatible with inverse discrete Fourier transform through utilization of the orthogonality between the pseudo-carriers. In the case where the optical transmitter 100 uses the optical transmitters $100_1$, ..., $100_K$ each of which is provided with filters of filtering characteristics phased $\pi/2$ apart for each period from the fundamental period to a period K/2 times the former, if the one of the $\pi/2$-phased-apart filtering characteristics in the optical transmitters $100_1$, ..., $100_K$ is a cosine function, the other is a sine function; the output from the optical transmitter 100 can be expressed by $\Sigma$(an cos((n/FSR) $\Theta$) + bn sin((n/FSR) $\Theta$)), where n is a value of a multiple of the filter period for the fundamental period, and an and bn are transmission signals that are carried by respective pseudo-carriers.

[0134] Even if the optical transmitter 100n and the optical receiver 200n are not provided which correspond to an arbitrary period n including the

fundamental period, since the value of an or bn concerned is a 0, the equation of the output from the optical transmitter 100 holds, and consequently the generality of this embodiment is not impaired.

Unlike ordinary WDM (Wavelength Division Multiplex) this

5   embodiment enables wavelengths to be superimposed on each other, and hence does not calls for the guard band needed in ordinary WDM, providing increased wavelength utilization efficiency.

Incidentally, the light sources 120 of the optical transmitters $100_1$, ..., $100_K$ may be replaced with a single light source.   While the Embodiment

10   2-11 uses multiple optical transmitters $100_1$, ..., $100_K$ utilizing pseudo-QPSK, it is also possible to use multiple optical transmitters utilizing the afore-mentioned pseudo-MPSK or pseudo-QAM.   Further, the filtering characteristic function is not limited specifically to the trigonometric function but may also be a function that has the properties referred to previously with

15   reference to Embodiment 2-9.   Accordingly, it is also possible to use pluralities of optical transmitters 100 and optical receivers 200 that use the chip-structured pseudo-carriers described previously with respect to Embodiments 2-5 to 2-8.   In this instance, assuming that S, which is a predetermined measure of L/4, is a reference S, optical transmitters $100_1$, ...,

20   $100_K$ and optical receivers $200_1$, ..., $200_K$ are used which are provided with filters each having a filtering characteristic based on S corresponding to the reference S.   That is, the reference S and the filtering characteristic S of each filter of the optical transmitters $100_1$, ..., $100_K$ correspond to the set of the fundamental and multiple periods generated by Fourier transform.   In this

25   way, the optical transmitter 100 of Embodiment 2-11 also sends the inverse-discrete-Fourier-transformed signal, and the optical receiver 200 discrete-Fourier-transforms the received signal into the original transmission

signal.

[0135] The filter for use in the optical transmitter of any embodiments described above may be a filter adapted to control its filtering characteristic by the modulator output as described previously in reference to Fig. 33;

5  alternatively, the filter may be configured to select a plurality of filters of fixedly set filtering characteristics.   Accordingly, to control the filter by the modulator means control of the filtering characteristic and control of selection of filters.

Since the signal-phase converter 110, the signal-to-phase and

10  amplitude converter 111 and the signal-amplitude converter 112 are to convert, in accordance with signal data, the input thereto to parameters for controlling filtering characteristics, selective control of filters and intensity control of light from the optical transmitter, they can generically be called signal-to-modulation value converters, and the phase amount and amplitude

15  amount output therefrom can be called modulated values, and their respective components can be referred to as parameters.

[0136] While the second mode of working of the invention, which performs MPSK or QAM by use of periodic functions on the optical frequency axis as mentioned above, has been described previously in relation to its general

20  configuration, but it can also be explained as follows.   Letting the optical frequency width $FSR_i$ represent a value obtained by dividing the optical frequency width FSR, which is the least common multiple, by an integer $N_i$ corresponding to the repetition period of the i-th optical frequency characteristic function $C_i(f)$ in the optical frequency width FSR in the optical

25  frequency range from the optical frequency Fst to Fla,

$$C_i(f) = C_i(f + FSR_i),$$

$$\int C_i(f) \cdot C_j(f) df > \int C_i(f) \cdot (1 - C_i(f)) df,$$

and for the j-th optical frequency characteristic function Ci(f) other than the i-th one,

$$\int Ci(f) \cdot Cj(f)df = \int Ci(f) \cdot (1 - Cj(f))df;$$

and letting $\Delta f$ represent the remainder of the division of the period FSRi of the function Ci(f) by an arbitrary optical frequency width equal to or narrower than Ci(f)FSR and a phase $2\pi$ ($\Delta f$/FSRi) represent the phase difference from Ci(f),

$$Ci'(f) = Ci(f + \Delta f),$$

that is, Ci'(f) is phased $2\pi(\Delta f$/FSRi) apart from Ci(f), and

$$\int Ci'(f) \cdot Cj(f)df = \int Ci'(f) \cdot (1 - Cj(f)) df;$$

an input binary data sequence is sequentially separated into multiple separate data sequences, and for each data of each separate data sequence in a repeating cyclic order, the phases or/and amplitudes of an i-th optical signal of the i-th optical frequency characteristic function and a j-th optical signal of the j-th optical frequency characteristic function are controlled in accordance with the value of said each piece of data, and the first and second optical signals thus obtained are combined by one or more light sources and transmitted therefrom as an optical code signal.

[0137] An example of the optical frequency characteristic function is a trigonometric function which has different FSRi and the same FSR but whose $\Delta f$ is FSRi/4 or $-$ FSRi/4.

Another example of the function Ci(f) is a function which divides FSR into a continuous optical frequency portion which is a value L, into which FSR is divided by 2SNi which is twice larger than the product of arbitrary integer S and Ni, and which repeats Ni times making S consecutive optical frequencies of each L-long optical frequency portion have the intensity 1 and the succeeding S optical frequencies have the intensity 0, or which

sequentially shifts the positions of the S consecutive optical frequencies of the intensity 1 by a predetermined amount.

[0138] The third mode of working of the invention is also applicable to the point-to-N point optical communication network PON shown in Figs. 2(a), 2(b), 3(a) and 3(b). It is also possible to apply to the third mode of working of the invention the technique of the first mode of working by which the i-th encoder on the monolithic planar lightwave circuit substrate controls the temperature of the planar lightwave circuit substrate which uses transmitted light through any one of the j-th decoders as described previously with reference to Figs. 15 and 28. Moreover, the optical encoding method of the first mode of working, which employs the arrayed waveguide AWG, described previously with reference to Figs. 21 and 22, is also applicable to the optical transmitter of the third mode of working.

[Third Mode of Working] [Reflective Optical Communication].

The third mode of working of the present invention is an application of the invention to a point-multipoint PON (Passive Optical Network) in which multiple subscriber terminals are connected to a central office via an optical fiber transmission lines, such an optical communications system as shown in Fig. 2 or 3.

[Embodiment 3-1]

A description will be given, with reference to Fig. 49, of the functional configuration of the basic concept of this third mode of working. Downstream signal light modulated (encoded) in accordance with binary data is input to a port 420a of an optical input/output unit 420 via an optical fiber 410 and then via an optical input/output port 412, thereafter being input to a switch 430 via a port 420b of the optical input/output unit 420. The switch 430 is controlled by an upstream data sequence from a terminal 431 to input

the downstream signal light to a mark encoder 440M or space encoder 440S.
The output light from the mark encoder 440 and th space encoder 440S is
input via an optical combiner 450 to a port 420C of the optical input/output
unit 420, and the input light is output as upstream signal light from the port

5      420a of the optical input/output unit 420 to the optical fiber 410 via the
optical input/output unit 412.   As the optical input/output unit 420 an optical
circulator is used as indicated by the broken line in Fig. 49, but an optical
directional coupler, an optical coupler/splitter, or the like may also be used.
However, in order to avoid intensity modulation of the upstream signal light

10     by a coherent crosstalk with reflected light and to reduce optical loss, the
optical input/output unit 420 may preferably be an optical circulator.   The
optical combiner 450 may be formed by an optical coupler/splitter or switch
that is controlled in interconnected control of the switch 430 as indicated by
the broken line; in short, the optical combiner needs only to input the output

15     light from the mark encoder 440M and the output light from the space
encoder 440S to the port 420 of the optical input/output unit 420.   The
switch 430 provides the input light to the mark encoder 440M or space
encoder 440S, depending on whether the data from the terminal 431 is the
mark or space.   In the case of using as the optical combiner 450 a switch

20     which is controlled by the data from the input terminal 431, the switch 430
may also be an optical splitter.
[0139] The mark encoder 440M and the space encoder 440S are formed, for
instance, as filters which output, over the entire period of the optical
frequency (wavelength) of the downstream signal light, optical signals that

25     are expressed by different functions each having the optical frequency
(wavelength) as a variable.   The optical frequency characteristics (optical
codes) of the input downstream signal light and the output upstream signal

light are functions that bear such relationship as described below.

Let a function of the optical intensity for the optical frequency f when the downstream signal light is mark, a function of the optical intensity when the downstream signal light is space, a function of the optical intensity for the

5    optical frequency f when the upstream signal light is mark, and a function of the optical intensity when the upstream signal light is space be represented by IM(f), IS(f), OM(f) and OS(f), respectively. The integration value of the product of the functions IM(f) and the function OM(f) with respect to f or summation of them and the integration value of the product of the functions

10    IM(f) and the function OS(f) with respect to f or the summation of them are equal, and the integration value of the functions IS(f) and the function OM(f) with respect to f or the summation of them and the integration value of the product of the functions IS(f) and the function OS(f) with respect to f or the summation of them are equal. That is, the functions bear the relationships

15    that satisfy either one of the following equations (22) and (23) and either one of the following equations (24) and (25).

[0140]
$$\int IM(f)\,OM(f)\,df = \int IM(f)\,OS(f)\,df \qquad (22)$$

$$\Sigma IM(f)\,OM(f) = \Sigma IM(f)\,OS(f) \qquad (23)$$

$$\int IS(f)\,OM(f)\,df = \int IS(f)\,OS(f)\,df \qquad (24)$$

20    $$\Sigma IS(f)\,OM(f) = \Sigma IS(f)\,OS(f) \qquad (25)$$

In the above, $\int df$ means the above-mentioned integral for an interval of the optical frequency period of the downstream signal, and $\Sigma$ means the above-mentioned summation for an interval of the optical frequency period of the downstream signal. The digital operations for Eqs. (22) and (24) are

25    similar to the operations for Eqs. (23) and (25).

[0141] These relationships indicate that the optical intensity of the mark function and the optical intensity of the space function are equal to each other

and that components corresponding to a half of the frequency components forming the mark or space downstream signal light can be formed as mark or space upstream signal light. Accordingly, this optical transmitter is capable of outputting the upstream signal light modulated by the same optical power

5 without lowering the modulation degree whether the downstream signal light be mark or space.

The above-mentioned functions may be such as shown in Fig. 6. Figs. 6(a) to (c) show examples of trigonometric functions, which are identical in amplitude, and overnormalized optical frequency period from 0 to

10 1 which is obtained through the optical frequency period from f0 to fL is normalized by the reference optical frequency f0 = fs, the numbers of intensity fluctuations contained in this optical frequency period are 1, 2 and 3, respectively; and one of the solid lines or broken lines phased $\pi/2$ apart, or the one-dot-chain line displaced about $\pi/4$ from the solid line as shown in Fig.

15 6(a) is used as the mark function and the function displaced $\pi$ apart therefrom is used as the space function; and for different directions or different optical communication equipment, another function bearing the relation shown in Figs. 6 is used as the mark function and a function phased $\pi$ apart therefrom is used as the space function. Alternatively, as shown in Fig. 50, the frequency

20 period from f0 to fL (normalized frequencies 0 to 1) is divided into L chips (optical frequencies), and when the function shown in Fig. 50(a) is, for instance, the mark function, the space function has the same number of chips of intensity 1 as that of the mark function as shown in Fig. 50(b), and a half of the intensity-1 chips of mark or space function of the downstream signal light

25 can be used for the upstream signal light. The first half of Fig. 50(b) is the same as the first half of Fig. 50(a), and the second half is an complementary version of the second half of Fig. 50(a). As an example of each chip the

optical intensity is shown in triangular form, but it is desirable that the optical frequency characteristic of each chip be in flat rectangular form.

[0142] As an encoder in the case of using a trigonometric function as the filtering function of the mark or space encoder 440M or 440S, it is possible to use such a Mach-Zehnder interferometer as depicted in Fig. 7 which is composed of a pair of optical paths 41 and 42 of different path lengths and couplers 43 and 44 coupled to both ends of the optical paths. Fig. 51 shows an example of the configuration of an encoder for forming, as the filtering function of the mark or space function 440M or 440S, such a chip string as shown in Fig. 50. The input light is fed to an optical filter 5, and the optical filter 5 outputs optical frequency signals of respective chips to different ports and outputs optical components displaced an integral multiple of the optical frequency $\Delta F$ apart. For example, when the output light from the encoder 440M or 440S repeats the same pattern every four chips, components of optical frequencies $F_1 + q\Delta F$, $F_2 + q\Delta F$, $F_3 + q\Delta F$ and $F_4 + q\Delta F$ (where $q = 1$, 2, …) are output from ports 1, 2, 3 and 4 of the optical filter 5, respectively. Of these outputs, the outputs from the ports corresponding to the chips of the intensity 1 are coupled by a coupler 6 and output therefrom. As such an optical filter 5, AWG (Arrayed Waveguide Graiting) can be used as is the case with the filter 84 in Fig. 21.

[0143] The switch 430 provides the input light to the mark encoder 440M or space encoder 440S, depending on whether the data from the terminal 431 is mark or space. When the optical combiner 450 is formed by a switch that is controlled by the data from the input terminal 431, the switch 430 may be an optical splitter. The upstream signal light and the downstream signal light may be transmitted over different optical fibers. For example, as indicated by the broken line in Fig. 49, provision may be made to input the upstream

signal light from the optical combiner 450 to an optical fiber 411, omitting the optical input/output unit 420.   Alternatively, as depicted in Fig. 52, total reflectors 451M and 451S are provided for total reflection of the optical outputs from the mark encoder 440M and the space encoder 440S so that the

5      optical outputs from the mark encoder 440M and the space encoder 440S pass through the mark encoder 440M and the space encoder 440S, respectively, and input via the switch 430 to the optical fiber 410.

[0144] The device configuration of Fig. 52 dispenses with the optical input/output unit 420 in Fig. 49 and the optical combiner 450, and hence

10     permits further reduction of the number of parts used; the number of parts for modulation is smaller than in the Fig. 49 configuration using a combination of switches, and as compared with the case of using a combination of a switch and an optical combiner instead of using two switches in Fig. 49, the illustrated device configuration produces the effect of avoiding the optical

15     loss by the optical combiner.

In Figs. 49 and 52 there is not shown a downstream signal light receiving circuit, but it is also possible that at a stage preceding the switch 430 a portion of the downstream signal light is branched to a downstream signal light receiving circuit to decode the downstream data sequence.

20     Reception and decoding similar to this will be described later on with reference to Fig. 53, for instance.   In the third mode of working of the invention, the light source is an optical transmitter of the communication partner which generates the downstream signal light (optical code signal).

[0145] As described above, according to this embodiment, light encoded by

25     one of the mark and the space equal in optical intensity to each other is received and a half of the optical frequencies forming the received mark or space downstream signal light is sent back as mark or space upstream signal

light.    Hence, light to be modulated as the upstream signal light can be supplied without the need for sending non-modulated CW light to be modulated as the upstream signal light separately of the downstream signal light and without impairing the extinction ratio of the downstream signal.

5    With the equipment disclosed in document 3, the central office separately sends the downstream signal light for sending its information (data) and non-modulated CW (Continuous Wave) light in the downstream direction so that the local office sends it back as an upstream signal modulated by information (data) of the local office itself.    As a result, the downstream

10    signal to be sent back to the central office is not actually used for information transmission therefrom.    With the equipment set forth in document 4, the central office purposely worsens the extinction ratio of the downstream signal light for sending the information (data) of the central office itself, and the local office modulates the received optical signal by the information (data) of

15    the local office itself and sends the modulated signal as the upstream signal light to the central office; hence inefficient continuous wave light is used. However, this degrades the extinction ratio of either of the downstream signal light from the central office and the upstream signal light from the local office, giving rise to the problem of deteriorated communication quality.

20    [0146] But the third mode of working of the invention permits modulation of the upstream signal light without the need for transmitting non-modulated light and without worsening the extinction ratio of the downstream signal light.    In the third mode of working of the invention, the encoder is encoding means which modulates, based on its encoding function, the optical signal so

25    that the optical intensity-frequency characteristic of the modulated optical signal becomes an optical intensity-frequency characteristic obtained by multiplying the optical intensity-frequency characteristic of the downstream

signal light by the optical intensity-frequency characteristic of the encoding function, and the decoder is decoding means which decodes and outputs, based on its decoding function, from the optical signal a component whose optical intensity-frequency characteristic is the decoding function.

5    [Embodiment 3-2]

Embodiment 3-2 is an example in which respective optical frequency characteristic functions made to be orthogonal to each other and to be chip codes.    Referring to Fig. 53, Embodiment 3-2 will be described below.    The downstream signal light from the optical fiber 410 is input to a downstream

10    mark decoder 464M and a downstream space decoder 461S via the optical input/output port 412, then the optical input/output unit 420 and then optical splitters 421 and 422, and light having passed through these decoders 461M and 461S is converted by optical detectors 470M and 470S into electrical signals; these electrical signals are compared by a comparator 480 to detect,

15    for example, the difference between them, and if the magnitude of the difference exceeds a predetermined value, it is provided as a downstream data sequence to an output terminal 481.

[0147] The other downstream signal light split by the first optical splitter 421 is input to the switch 430, and as shown in Fig. 49, it is modulated by the

20    upstream data sequence from the input terminal 431 into the upstream signal light, which is fed to the optical input/output unit 420, from which it is output via the optical input/output port 412 to the optical fiber 410.    When the optical combiner 450 is formed by a switch which is controlled by the data from the terminal 431, the switch 430 may be substituted with an optical

25    splitter.

In Embodiment 3-1 an integration value of the difference obtained by subtracting the space upstream signal light from the mark upstream signal

light and the mark or space downstream signal light, with respect to an optical frequency, or the summation of them is zero; that is, the optical characteristic functions of them are made to apparently be orthogonal to each other. More specifically, the downstream signal light is a natural- number NI set of input light which has an optical frequency characteristic identical with the optical frequency function of either one of the mark and space; letting the optical intensity functions of the i-th mark and space be represented by $IMi(f)$ and $ISi(f)$, respectively, the relationship between the i-th downstream signal light and a j-th downstream signal light other than the i-th one both contained in the NI sets satisfies the following equation (26) or (27).

[0148] $\int IMi(f)(IMj(f) - ISj(f))\, df = \int ISi(f)(IMj(f) - ISj(f))\, df =$
$\int IMj(f)(IMj(f) - ISi(f))\, df = \int ISj(f)\,(IMi(f) - ISj(f))\, df = 0$ (26)

$\Sigma IMi(f)(IMj(f) - ISj(f)) = \Sigma ISi(f)(IMj(f) - ISj(f)) = \Sigma IMj(f)(IMi(f) - ISi(f)) = \Sigma ISj(f)(IMi(F) - ISi(f)) = 0$ (27)

And, the relationship between the i-th downstream signal light and the i-th upstream signal light contained in the NI set satisfies the following equation (28) or (29).

[0149] $\int IMi(f)(OMi(f) - OSi(f))\, df = \int ISi(f)(OMi(f) - OSi(f))\, df =$
$\int OMi(f)(IMi(f) - ISi(f))\, df = \int OSi(f)\,(IMi(f) - ISi(f))\, df = 0$ (28)

$\Sigma IMi(f)(OMi(f) - OSi(f)) = \Sigma ISi(f)(OMi(f) - OSi(f)) = \Sigma OMj(f)(IMi(f) - ISi(f)) = \Sigma OSi(f)(IMi(F) - ISi(f)) = 0$ (29)

In the above, $\int$ means the above-mentioned integral for an interval of the optical frequency period of the downstream signal, and $\Sigma$ means the above-mentioned summation over the optical frequency period of the downstream signal. Incidentally, the downstream signal light to be detected in the same optical communication equipment and the upstream signal light to be output therefrom have different functions. The digital operations for Eqs.

(26) and (28) are similar to the operations for Eqs. (27) and (29).

[0150] As the function having such properties as mentioned above, it is possible to use the Hadamard codes such as shown in Fig. 10. The optical frequency characteristic function of the signal light, if used as the filtering function, is such that, for example, for the mark signal light, the optical frequency chip 1 is allowed to pass but the optical frequency chip 0 is not allowed, whereas for the space signal light the optical frequency chip 1 is not allowed to pass but the optical frequency chip 0 is allowed. That is, in the case of the same code, the optical intensities 1 and 0 are reversed between the mark signal light and the space signal light. The code 2 [0101], the code 3 [0011] and the code 4 [0110] satisfy Eqs. (22) to (29). For example, in order to generate the signal light of the code 2 [0101], the ports of the optical filter 5 from which to output optical wavelengths (optical frequencies) $\lambda_2$ and $\lambda_4$ are connected to the coupler 6 as shown in Fig. 51, the ports from which to output optical wavelengths (optical frequencies) $\lambda_1$ and $\lambda_3$ are connected to the port 6' as indicated by the broken lines, and the outputs from the couplers 6 and 6' are selectively output from the switch 450 serving as an optical combiner, depending on whether the data is mark or space..

[0151] Because of such codes, for example, when an i-th signal light is to be received but a different signal light, for instance, a j-th one is actually input, the filtering characteristic functions of the downstream mark decoder 461M and the downstream space decoder 461S are IMi(f) and ISi(f), respectively, and the optical frequency functions of the input light is IMj(f) or ISj(f), and Eqs. (26) or (27) holds; consequently, the difference between the detected optical intensities of the outputs from the decoders 461M and 461S is cancelled in the comparator, so that signal light other than the i-th one to be received is not provided to the output terminal 481. Further, the filtering

characteristic functions of the upstream mark encoder 441M and the upstream space encoder 441S are OMi(f) and OSi(f), respectively, and even if the upstream signal is reflected on the optical transmission line and the reflected light is input to the downstream mark decoder 461M and 461S, Eq. (28) or

5    (29) holds; accordingly, the detected optical intensities by the optical detectors 470M and 470S are cancelled by the comparator 480 and no output therefrom is provided to the output terminal 481.   In other words, even if reflected light exists, it does not constitute any obstacle to the reception of signal light of the desired code.

10    [0152] Other examples of functions having such characteristics will be described below.   The optical frequency period from f0 to fL (normalized optical frequencies) of the downstream signal light is divided into L = 4s as shown in Fig. 54(a), for instance; the i-th mark function Mi(f) repeats n = 2 times transmission (optical intensity 1) of the first s chips and no-transmission

15    (optical intensity 0) of the succeeding s chips, and the i-th space function Si(f) repeats n = 2 times transmission (optical intensity 1) of the first s chips and non-transmission (optical intensity 0) of the succeeding s chips.   When the period f0 to fL is divided into L = 6s as shown in Fig. 54(b), the i-th mark function Mi(f) repeats n = 3 times transmission of the first s chips and

20    non-transmission of the next s chips, and the i-th space function Si(f) repeats n = 3 times transmission of the first s chips and no-transmission of the next s chips.   In general, the function mentioned herein is the filtering characteristic function (optical intensity-frequency characteristic function) represented by the optical frequency of L chips into which the optical frequency period from

25    f0 to fL is divided, the number obtained by dividing L by 2 being a multiple of s; letting IMi(f) represent the filtering characteristic function for the i-th mark and ISi(f) represent the filtering characteristic function for the i-th space,

the i-th filtering characteristic function IMi(f) is a function that repeats transmission of s chips and non-transmission of the succeeding s chips at least the number of times (n times) obtained by dividing L by 2s, and the i-th filtering characteristic function ISi(f) is a function that repeats

5   non-transmission of s chips and transmission of the succeeding s chips at least the number of times (n times) obtained by dividing L by s.   Incidentally, the illustrated functions start transmission or non-transmission of consecutive s chips at f0, but in such a case as shown in Fig. 54(c) where L = 6s and n = 3, the function may also be one that starts transmission or non-transmission of

10   chips of an arbitrary integer s smaller than s, then repeats non-transmission or transmission of s chips and transmission or non-transmission of the succeeding s chips the number of times obtained by subtracting 1 from a number obtained by dividing L by 2s, followed by transmission or non-transmission of (s − s0) chips.   That is, despite of the above-mentioned

15   relationship, the function may be such a function as shown in Fig. 54(c) which is phased apart from the function of Fig. 54(b), for instance.   The code 2 of the afore-mentioned second-order Hadamard matrix is L = 4, s = 1 and n = 2, the code 3 is L = 4, s = 2 and n = 1, and the code 4 is a cyclically left shifted version of the code 3 by the phase $\pi/4$.   These relationships are the

20   same as the characteristic functions shown in Embodiment 2-6 of the second mode of working of the invention; for example, IMj(f), ISi(f), OMj(f), and DSj(f) correspond to Ci(f), (1 − Ci(f)), Cj(f) and (1 − Cj(f)), respectively.

[0153] It will easily be seen that these filtering characteristics, the encoders 441M and 441S and the decoders 461M and 461S which have such functions

25   can be similarly implemented by use of such optical filter 5 and couplers 6 and 6' as shown in Fig. 51.   In the case of using the encoder of such a configuration as mentioned above, the upstream mark encoder 441M and the

upstream space encoder 441S are formed integral as an upstream encoder as indicated by the one-dot-chain line in Fig. 53, the switch 430 is omitted, the optical combiner 450 is formed by a switch, the downstream mark decoder 461M and the downstream space decoder 461S are also formed integral as a

5    downstream decoder 461, and the optical splitter 422 is omitted.

[0154] In Embodiment 3-2 depicted in Fig. 53, too, as is the case with the Fig. 52 embodiment, the provision of total reflectors 451M and 451S at the output sides of the upstream mark encoder 441M and the upstream space encoder 441S permits removal of the optical input/output unit 420 and the optical

10   combiner 450, allowing reduction of the number of parts used.    Moreover, it is also possible to form the switch 430 by an optical splitter and the optical combiner 450 by a switch.

Fig. 55 illustrates an example of the configuration of optical communication equipment that is the communication partner of the optical

15   communication equipment shown in Fig. 53.    The optical signals of the optical frequencies f0 to fL from a light source 495 are switched by a switch 435 between a downstream mark encoder 445M and a downstream space encoder 445S, depending on whether each piece of data of a downstream data from an input terminal 436 is mark or space.    The filtering characteristic

20   functions of the downstream mark encoder 445M and the downstream space encoder 445S are chosen to be the same as the filtering characteristic functions $IMi(f)$ and $ISi(f)$ of the downstream mark decoder 461M and the downstream space decoder 461S of the partner optical communication equipment.    The downstream signal light from the downstream mark

25   encoder 445M and the downstream space encoder 445S is input via an optical combiner 455 and an optical input/output unit 425 to the optical fiber 410.

[0155] The upstream signal light input from the optical fiber 410 is input via

the optical input/output unit 425 and an optical splitter 426 to an upstream mark decoder 465M and an upstream space decoder 465S. The filtering characteristic functions of the decoders 465M and 465S are chosen to be the same as the filtering characteristic functions OMi(f) and OSi(f) of the

5     upstream mark encoder 441M and the upstream space encoder 441S of the partner optical communication equipment. The output signal light from the upstream mark decoder 465M and the upstream space decoder 465S is input to optical detectors 475M and 475S, and output electrical signals from the optical detectors 475M and 475S are compared by a comparator 485, which

10     provides its compared output as an upstream data sequence to an output terminal 486.

[0156] According to Embodiment 3-2, even if multiple pairs of optical communication equipment that outputs the downstream signal light and the optical communication equipment that outputs the upstream signal light

15     shares the optical fibers 410, since each pair uses different codes (filtering functions), that is, the optical frequency characteristic functions bearing the afore-mentioned relationship, optical signals from optical communication equipment other than the pair of equipment also are orthogonal to each other and hence they do not become noise, and since the downstream signal light

20     and the upstream signal light are also different in code, at least one-half of the optical frequency components of the downstream signal lights can be modulated as upstream signal light. This effect is particularly effective in a PON (passive Optical Network) configuration that is a point-to-N point network such as defined in ITU-T Recommendation G. 983 and G. 984 series.

25     In a wavelength division multiplex-passive optical network (WDM-PON) of the type heretofore proposed, downstream signal lights that are sent to optical network units (ONU) which are other customer premises equipment is usually

mere noise, that is, noise that is merely discarded by an optical filter or the like.   In Embodiment 3-2, however, it can be effectively used as lights for modulation as the upstream signal light.   In the case of making an optical intensity design on the presumption of making use of the downstream

5   communication lights to other optical network unit, if the number of optical network units to be connected is too small to secure downstream signal light of sufficient optical intensity, it is necessary for the partner optical communication equipment to output downstream light corresponding to the number of unconnected optical network units.

10   [Embodiment 3-3]

Embodiment 3-3 uses trigonometric functions as the functions which have the relationship of Eq. (22) or Eq. (23), Eq. (24) or Eq. (25), Eq. (26) or Eq. (27), and Eq. (28) or Eq. (29).   That is, the functions for use in Embodiment 3-3 are trigonometric functions that bear integral-multiple

15   relations between their period of optical intensity variation in the optical frequency region or are phased $\pi/2$ apart when the periods of optical intensity variation in the optical frequency region when the periods are the same. That is, the optical frequency characteristic function $Mi(f)$ of the mark signal light, for instance, is given by Eq. (30)

20   $$Mi(f) = (1 + \cos2\pi sf/(fL - f0) + r\pi/2))/2 \qquad (30)$$

And the optical frequency characteristic function $Si(f)$ of the space signal light is $1 - Mi(f)$, that is, given by Eq. (31).

[00157] $Si(f) = 1 - (1 + \cos(2\pi sf/(fL - f0) + r\pi/2)) \qquad (31)$

where s is an integer in the range from 1 to a value $NI/2$ obtained by dividing

25   the maximum NI (required number of codes) by 2, r is 0 or 1, and $fL - f0 = FSR$.   In Fig. 6, (a), (b) and (c) are trigonometric functions which corresponds to $s = 1, 2$ and 3 of $Mi(f)$, respectively, the dotted lines

corresponding to r = 0 and the solid lines corresponding to r = 1.

The filter of such an optical frequency characteristic function can easily be formed by the Mach-Zehnder interferometer shown in Fig. 7, for instance. Fig. 56 illustrates an example of the optical communication

5   equipment in such a case. The downstream signal light from the optical fiber 410 is input via the optical input/output unit 420 to the downstream decoder 461 and the upstream encoder 441 after being split by the optical splitter 421. The downstream decoder 461 and the upstream encoder 441 are each formed by the Mach-Zehnder interferometer. The optical path length

10  differences between the optical paths 41 and 42 of the Mach-Zehnder interferometers forming the decoder 461 and the encoder 441 are determined corresponding to the functions IMi(f) and OMi(f), respectively. Assuming that mark signal light is output from the one output port of the coupler 44 of the decoder 461, space signal light is output from the other output port, and

15  the optical outputs are input to the optical detectors 470M and 470S, respectively. On the other hand, mark signal light from the one output port and space signal light from the other output port of the coupler 44 of the encoder 441 are provided to the switch 450. The illustrated optical communication equipment is identical in construction and operation to the Fig.

20  53 equipment except the above.

[0158] The use of such trigonometric functions also provides orthogonality between respective codes, eliminates interference by other codes and excludes the influence of reflected light, and in the point-to-N point access network or the like the downstream signal lights from optical communication equipment

25  other than the partner one can also be used as light for modulation as the upstream signal light; thus, this embodiment produces the same effects as are obtainable with Embodiment 3-2.

[Embodiment 3-4]

Embodiment 3-4 is provided with an optical amplifier with a view to implementing any one or all of: a solution to insufficient optical intensity of the downstream signal light; reception of the downstream signal light with the optical intensity within the dynamic range of the optical detector; and outputting of the upstream signal light with a sufficient optical intensity.

[0159] As indicated by the broken line in Fig. 53, an optical amplifier 423 is inserted between the optical input/output unit 420 and the optical splitter 421 to amplify the downstream signal light.   The optical amplifier 423 amplifies input light from both directions; for example, SOA (Semiconductor Optical Amplifier) can be used.   In this instance, the optical amplifier 423 may be inserted in the optical fiber 410 as indicated by the broken line to amplify both of the downstream signal light and the upstream signal light. Alternatively, optical amplifiers 423a and 423b may be connected to the two split output sides of the optical splitter 421, respectively, and the amplification factor of the optical amplifier 423a is chosen so that the downstream signal light for reception use has an optical intensity in the dynamic range of each of the optical detectors 470M and 470S, whereas the amplification factor of the optical amplifier 423b for amplifying the downstream signal light for transmission use so that the upstream signal light has a sufficient level of optical intensity.   The optical amplifier 423b may be connected to the output side of the optical combiner 450.   In this instance, the amplifier amplifies only light encoded by the encoder 441M and 441S, and hence effectively amplifies them.   Similarly, when optical amplifiers 423aM and 423bS are connected to the output sides of the downstream mark decoder 461M and the downstream space decoder 461S in place of the optical amplifier 423a, only decoded signal light can be amplified efficiently, and the optical amplifier

423aM for mark and the optical amplifier 423aS for space can also be used as independent hard limiters.

[0160] The optical combiner 450 may be configured as shown in Fig. 57, in which the optical signal outputs from the upstream mark encoder 441M and

5     the upstream space encoder 441S are combined by an optical combiner 453 after being amplified by optical amplifiers 452M and 452S, respectively, and the amplification factors of the optical amplifiers 452M and 452S are controlled according to the data from the terminal 431 to selectively output coded light corresponding to mark and space, by increasing the amplification

10    factor of the optical amplifier 452M but decreasing the amplification factor of the optical amplifier 452S when the data from the input terminal 431 is mark and by decreasing the amplification factor of the optical amplifier 452M but increasing the amplification factor of the optical amplifier 452S when the data is space.   In this way, the optical intensity of the upstream signal light can be

15    increased sufficiently.   In this case, an optical splitter can be used instead of the switch 430.   This produces the effect of eliminating the need for using switches in the optical communication equipment.   While in the above an embodiment of the optical communication equipment of Fig. 53 has been described as using the optical amplifier, the filtering characteristic functions

20    of the encoder and the decoder for use in the optical communication equipment may be not only the optical frequency chip sequence functions but also the trigonometric functions described previously with reference Embodiment 3-3.   Furthermore, optical amplifiers can similarly be used to effectively work even if they are inserted at respective places in the optical

25    communication equipment in which total reflectors are provided at the output sides of the encoders, the optical input/output unit 420 is omitted and the downstream signal light is decoded as shown in Fig. 52.   Fig. 58 illustrates

an example of such optical communication equipment, in which insertable optical amplifiers are indicated by the broken lines and identified by the same reference numerals as those in Figs. 52, 53 and 57, and no description will be given of them.    In this instance, the optical splitter connected directly to the

5      optical input/output port 412 is formed by an optical combiner/splitter 421, and in the case of selecting the mark signal light and the space signal light by controlling, according to data, the amplification factors of the optical amplifiers 451M and 451S connected to the sides opposite to the total reflectors 451M and 451S with respect to the mark encoder 441M and the

10     space encoder 441S, the switch 430 is formed by an optical combiner/splitter. In the case where the mark encoder 441M and the space encoder 441S are formed by a single-structured encoder 441, the optical amplifiers 451M and 451S are inserted between the mark signal light output port and the space signal light output port of the encoder 441 and the total reflectors 451M and

15     451S, respectively, and in the case of controlling these optical amplifiers 451M and 451S according to the upstream data sequence, the input port of the encoder 441 is connected directly to the optical combiner/splitter 421, and consequently the optical combiner/splitter 430 can be omitted.    In this case, the optical amplifiers 451M and 451S may be substituted with switches which

20     are ON/OFF-controlled inversely to each other according to the upstream data; to sum up, they need only to select either one of the mark signal light and the space signal light in accordance with the upstream data.

[Embodiment 3-5]

        While in the above the receiving decoder circuit for the downstream

25     signal light and the transmitting encoder circuit for the upstream signal light are provided in parallel, they may be provided in tandem.    Referring now to Fig. 59, Embodiment 3-5 will be described below in which the transmitting

encoder circuit is disposed near the optical input/output port 412, that is, on the side of the optical fiber 410, and the receiving decoder circuit is connected in cascade to the transmitting encoder circuit.

[0161] To the optical input/output port 412 is connected the optical

5    combiner/splitter 430 via an optical amplifier 442 as required.    Accordingly, the downstream signal light from the optical fiber 410 is input via the optical combiner/splitter 430 to the encoders 441M and 441S.    As referred to previously, the mark signal light and the space signal light are complementary to each other in the optical intensity of each optical frequency and equal in the

10   mean optical intensities in the optical frequency range from f0 to fL, and the optical frequencies corresponding to one-half the optical frequency components forming the mark signal or space signal light in the downstream signal light are utilized to form the mark signal light or space signal light as the upstream signal light.

15        Accordingly, the half of the effective optical frequency components in the downstream signal light passes through the encoders 441M and 441S, and these transmitted optical outputs are combined by the switch 450 and input to an optical combiner/splitter 424, wherein it is split for input to the total reflector 451 and the optical splitter 422.    The downstream signal light input

20   to the optical splitter 422 is split into two for input to the decoders 461M and 461S.    If the optical frequency characteristic of this downstream signal light is matched to the filtering characteristic function of the decoder 461M or 46aS, the optical frequency components, which is at least one-half those in the downstream signal light in the optical fiber 210 as described previously

25   correctly pass through the decoder, providing decoded data from the comparator 480.

[0162] On the other hand, the light reflected off the total reflector 451 is input

via the optical combiner/splitter 424 to the optical combiner 450. Since the switch 450 is controlled by the upstream data sequence from the terminal 431, the signal light encoded when the downstream signal light having passed through the encoder 441M or 441S previously is reflected off the total

5 reflector 451, then subjected to the same encoding, and input to the optical combiner/splitter 430, from which it is input as the upstream signal light to the optical fiber 410. This upstream signal light is encoded twice by the encoder 441M or 441S and this encoding is based on the same characteristic, but there is a fear of the final encoding of the upstream signal light being

10 affected by the preceding light encoded at the time of passage through the switch 450 from the optical fiber 410 and reflected by the total reflector 451--this incurs the possibility of the optical frequency characteristic of the upstream signal light being disturbed. This can be avoided by amplifying the upstream signal light for input to the optical fiber 410 by the optical

15 amplifier 442 until it is saturated. However, this is limited specifically to the case of using a chip sequence as the function of the signal light. It is also possible to exchange the optical combiner/splitter 430 for a switch and the switch 450 for an optical combiner/splitter. Furthermore, the afore-mentioned various modifications may similarly be effected. The

20 switch 450 may be configured as shown in Fig. 57, in which the upstream signal light for input to the optical fiber 410 is saturation-amplified by the optical amplifiers 452M and 452S as a substitute for the optical amplifier 442. Furthermore, the optical amplifier 442 may be disposed at the stage preceding the total reflector 451 as indicated by the broken line in Fig. 59. In this

25 instance, the optical amplifier and the total reflector can be formed as a unitary part by giving total reflection coating to one end of SOA.

[Embodiment 3-6]

Embodiment 3-6 omits the optical combiner/splitter 424 and the total reflector 451 in Embodiment 3-5 as shown in Fig. 60, for instance.    The downstream signal light having passed through the encoders 441M and 441S is input via the switch 450 to a partial reflector 454, and one portion of the

5    downstream signal light is reflected by the partial reflector 454 and the remaining portion of the signal light passes through the partial reflector and enters the optical splitter 422.    In this instance, too, it will easily be understood that the downstream signal light can be correctly decoded and that one portion of the downstream signal light can be used to generate the

10    upstream signal light.    As compared with the case of Fig. 59, this embodiment dispenses with the optical combiner/splitter 424, producing the effect of eliminating the loss in the optical combiner/splitter 424.    As indicated by the broken line, the optical amplifier 442 may be disposed between the partial reflector 454 and the switch 450.    In this case, by

15    depositing, for example, one end of SOA with a partial reflection coating, the optical amplifier and the partial reflector can be formed in a one-piece structure.    The switch 450 may be configured as shown in Fig. 57, in which the optical amplifiers 451M and 451S are used also as the optical amplifier 442.    Moreover, the afore-mentioned various modifications can similarly be

20    effected.

[Embodiment 3-7]

In this embodiment a transmitter circuit is connected in cascade to the output side of a receiver circuit.    As the optical detectors 470M and 470S in the receiver circuit, optical detectors 471M and 471S are used which are

25    formed by optical amplifiers capable of taking out electrical signals proportional to the input optical intensity, as shown in Fig. 61.    For example, SOAs can be used as the optical detectors 471M and 471S, and the electrical

signal from the optical detectors 471M and 471S, which are proportional to the optical intensities of the respective optical outputs from the mark decoder 461M and the space decoder 461S, are input to the comparator 480. On the other hand, the amplified optical signals from the optical detector 471M and

5    471S are combined by an optical combiner/splitter 472, and the combined output is input to the switch 430. The other configurations and operations are the same as those in Fig. 53. In this instance, too, since the optical frequency characteristics of each mark signal light and space signal light are formed as described previously, the signal light having passed through the

10    downstream decoder 461 contains optical frequency components corresponding to the half of those of the downstream signal light, and the upstream mark signal light or upstream space signal light can be generated by the upstream encoder 441. With this configuration, the optical splitter 421 for separating the downstream signal light to the receiving side and the

15    transmitting side in the configuration of Fig. 53 becomes unnecessary, and the downstream signal light for input to the encoders 441M and 441S can be amplified by the optical detectors 471M and 471S.

[0163] Fig. 62 illustrates an embodiment which uses the optical amplifiers 471M and 471S as optical detectors in the case of using Mach-Zehnder

20    interferometers as the downstream decoder 461 and the upstream encoder 441 as depicted in Fig. 56. The downstream signal light from the optical input/output unit 420 is input directly to the downstream decoder 461, and the decoded downstream mark signal and downstream space signal from the downstream decoder 461 are input to the optical detectors 471M and 471S

25    formed by optical amplifiers, respectively. The electrical signals proportional to the optical intensities of the inputs to the optical detectors 471M and 471S are input to the comparator 480, and the mark signal light and

the space signal light amplified by the optical detectors 471M and 471S are input to a correcting combiner 473 formed by a Mach-Zehnder interferometer having its port exchanged with that of the Mach-Zehnder interferometer forming the downstream decoder 461. The difference in the optical path

5    length between the optical paths 41 and 42 in the downstream decoder 461 is corrected by the difference in the optical path length between the optical paths 41 and 42 in the correcting combiner 471, and the downstream mark signal light and the downstream space signal light are combined by the coupler 44 after passing through optical paths of the same length. The combined

10   downstream signal light is input to the encoder 441 formed by the Mach-Zehnder interferometer. The other configurations and operations are the same as shown in Fig. 56. Since the optical outputs from the optical detectors 471M and 471S are combined by the Mach-Zehnder interferometer, the loss can be reduced as compared with that in the case of using the optical

15   multiplexer 47 in Fig. 61.

[0164] Given below is a general description of the third mode of working of the invention. This mode of working is predicated on the optical communications system which: transmits the downstream signal light from the optical transmitter; receives the downstream signal light by reflective

20   optical communication equipment; regenerates the downstream data sequence through utilization of part of the received downstream signal light; and modulates part of the received downstream signal light into the upstream signal light and transmits it to the above-mentioned optical transmitter.

In this third mode of working of the invention, functions and their

25   complementary functions need not always to be periodic. Accordingly, the optical intensity-frequency characteristic of the received optical code signal has the function Ci(f) or Ck(f) and the filtering frequency characteristic, the

upstream encoder 441 is $Cj(f)$ or $Cm(f)$, and these functions satisfy the following equations that express the scalar-product integration values for the interval of the optical frequency width FSR in an arbitrary range from the optical frequency Fst to Fla.

5
$$\int Ci(f) \cdot Cj(f)\, df = \int Ci(f) \cdot Cm(f)\, df$$
$$\int Ck(f) \cdot Ci(f)\, df = \int Ck(f) \cdot Cm(f)\, df$$

But it is not always required that $Ck(f) = (1 - Ci(f))$ and $Cm(f) = (1 - Cj(f))$. In the case were $Ck(f) \neq (1 - Ci(f))$, however, $(1 - Ci(f))$ and $(1 - Ck(f))$ are not used in the same system. Similarly, when $Cm(f) \neq (1 - Cj(f))$,

10
$(1 - Cj(f))$ and $(1 - Cm(f))$ are not used in the same system.

[0165] Furthermore, at least one of the scalar-product integration values $\int Ci(f) \cdot Cj(f)\, df$ and $\int Ck(f) \cdot Ci(f)\, df$ is not zero. That is, either $Ci(f) > 0$ or $Ck(f) > 0$ holds.

When the functions $Ci(f)$ and $Cj(f)$ are periodic, it becomes as follows.

15
Letting a common multiple of the repletion period FSRi of the function of each code in the optical frequency range from the optical frequency Fst to Fla be represented by the optical frequency width FSR and a value obtained by dividing the optical frequency width FSR by a common multiple of the function repetition period FSRi be represented by the optical

20
frequency width FSRi,
$$Ci(f) = Ci(f + FSRi),\ and$$
$$\int Ci(f) \cdot Ci(f)\, df > \int Ci(f) \cdot (1 - Cj(f))\, df;$$

for the j-th optical frequency characteristic function $Cj(f)$ other than the i-th one,

25
$$\int Ci(f) \cdot Cj(f)\, df = \int Ci(f) \cdot (1 - Cj(f))\, df.$$

Based on the optical frequency characteristic functions bearing such relationships, for each piece of data of the binary data sequence the optical

frequency characteristic function of the received downstream signal light is made $Ci(f)$ or $(1 - Ci(f))$, depending on whether said piece of data is mark or space.   One portion of this downstream signal light is allowed to pass through the decoders whose filtering characteristic functions are $Ci(f)$ and $(1 - Ci(f))$, and the optical intensities of the transmitted optical outputs are detected, and the received downstream signal light is regenerated as the mark or space in accordance with the difference between the detected optical intensities.

[0166] And, for each piece of data of the upstream data sequence, the optical frequency characteristic of one portion of the downstream signal light is modulated by an encoder to $Cj(f)$ or $(1 - Cj(f))$, or $(1 - Cj(f))$ or $Cj(f)$, depending on whether said each piece of data is mark or space, and the downstream signal light is transmitted as an upstream signal light.